JOINING

UNDERSTANDING
THE
BASICS

Edited
by
F.C. Campbell

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Contents

Preface

This book is a rather brief introduction to industrial joining processes. The intent was to take an extensive amount of technical information on the individual joining processes and boil it down to provide a readable resource on joining. The majority of the information in this book was extracted from the *ASM Handbook* series. The book covers all of the major welding processes; brazing and soldering; mechanical fastening; and adhesive bonding.

Welding is a process that joins materials, usually metals or thermoplastics, by causing coalescence. This is often done by melting the workpieces and adding a filler material to form a pool of molten material (the weld pool) that cools to become a strong joint, with pressure sometimes used in conjunction with heat, or by itself, to produce the weld. No other technique is as widely used as welding to join metals and alloys efficiently and to add value to their products. Most of the familiar objects in modern society, from buildings and bridges, to vehicles, computers, and medical devices, could not be produced without the use of welding.

Until the end of the 19th century, the only welding process was forge welding, which blacksmiths had used for centuries to join iron and steel by heating and hammering them. Arc welding and oxyfuel welding were among the first processes to develop late in the century, and resistance welding followed soon after. Welding technology advanced quickly during the early 20th century as World War I and World War II drove the demand for reliable and inexpensive joining methods. Following the wars, several modern welding techniques were developed, including manual methods like shielded metal arc welding, now one of the most popular welding methods; as well as semiautomatic and automatic processes such as gas metal arc welding, submerged arc welding, flux-cored arc welding and electroslag welding. Developments continued with the invention of laser beam welding and electron beam welding in the latter half of the century. Today, the science continues to advance. Robot welding is becoming more commonplace in industrial settings, and researchers continue to develop new welding methods and gain greater understanding of weld quality and properties. Welding today is applied to a wide range of materials and products, using such advanced technologies as lasers and plasma arcs.

After an introduction to the various joining processes (Chapter 1), the next five chapters address different welding processes. It is estimated that 90% of all industrial welding is done by arc welding The arc welding processes covered in Chapter 2 include shielded metal arc welding, flux-cored arc welding, submerged arc welding, gas metal arc welding, gas tungsten arc welding, plasma arc welding, plasma-MIG welding, and electroslag welding and electrogas welding.

Resistance welding is a group of processes in which the heat for welding is generated by the resistance to the flow of an electrical current through the parts being joined. It is most commonly used to weld two overlapping sheets or plates that may have different thicknesses. Specific resistance welding processes covered in Chapter 3 include resistance spot welding, resistance seam welding, projection welding, flash welding, and upset welding.

The other fusion welding processes that were not covered in Chapters 2 and 3 are covered in Chapter 4. These include oxyfuel gas welding, oxyacetylene braze welding, stud welding (stud arc welding and capacitor discharge stud welding), high-frequency induction welding, electron beam welding, laser beam welding, and thermite welding.

Some of the metallurgical variables in fusion welding are reviewed in Chapter 5. These include energy intensity, heat flow, weld pool solidification, solid-state transformations after solidification, residual stresses and distortion, distortion control, welding discontinuities, weld cracking, fatigue strength of weldments, and inspection of welded joints.

Solid-state welding processes (Chapter 6) are those that produce coalescence of the faying surfaces at temperatures below the melting point of the base metal being joined without the addition of brazing or solder filler metal. Pressure may or may not be applied. These processes involve either the use of deformation or of diffusion and limited deformation in order to produce high-quality joints between both similar and dissimilar materials. Specific solid-state welding processes include: diffusion bonding, forge welding, roll welding, coextrusion welding, cold welding, friction welding and friction stir welding, explosive welding, and ultrasonic welding.

Brazing and soldering processes, covered in Chapter 7, use a molten filler metal to wet the mating surfaces of a joint, with or without the aid of a fluxing agent, leading to the formation of a metallurgical bond between the filler and the respective components. Solders usually react to form intermetallic phases, that is, compounds of the constituent elements that have different atomic arrangements from the elements in solid form. By contrast, most brazes form solid solutions, which are mixtures of the constituents on an atomic scale. Joining processes of this type are defined as soldering if the filler melts below 450 °C (840 °F) and as brazing if it melts above this temperature.

A mechanical fastener is a hardware device that mechanically joins or affixes two or more objects together. The concept of the screw was described by the Greek mathematician Archytas of Tarentum (428-350 BC). Mechanical fastening is the subject of Chapter 8. One unique feature of mechanical fastening is that the joint can either be permanent (e.g., riveting) or temporary (e.g., screws). Many types of fasteners and fastening systems have been developed for specific requirements, such as high strength, easy maintenance, corrosion resistance, reliability at high or low temperatures, or low material and manufacturing costs. Fastener types discussed include threaded fasteners (bolts and screws), pin and collar fasteners, rivets, blind fasteners, and miscellaneous fastening methods such as stitching, stapling, snap fits, and integral fasteners.

An adhesive (Chapter 9) is a polymeric mixture in a liquid or semiliquid state that adheres or bonds items together. Adhesives may come from either natural or synthetic sources. The types of materials that can be bonded are vast but they are especially useful for bonding thin materials. Adhesives cure (harden) by either evaporating a solvent or by chemical reactions that occur between two or more constituents. Adhesives are advantageous for joining thin or dissimilar materials, minimizing weight, and when a vibration dampening joint is needed.

While adhesive bonding is often thought of as a relatively new technology, the oldest known adhesive, dated to approximately 200,000 BC, is from spear stone flakes glued to a wood with birch-bark-tar, which was found in central Italy. The use of compound glues to attach stone spears into wood dates back to round 70,000 BC. Evidence for this has been found in Sibudu Cave, South Africa and the compound glues used were made from plant gum and red ochre. The Tyrolean Iceman had weapons fixed together with the aid of glue.

A number of materials and material combinations are difficult to join, either because of their individual chemical compositions or because of large differences in physical properties between the two materials being joined. In any dissimilar joining process high temperatures, differences in the coefficients of thermal expansion (CTEs) are a major consideration. In Chapter 10, a number of these situations are covered: welding of dissimilar metal combinations; joining of plastics by mechanical fastening, solvent and adhesive bonding, and welding; joining of thermoset and thermoplastic composite materials by mechanical fastening, adhesive bonding, and for thermoplastic composites, welding; the making of glass-to-metal seals; and joining of oxide and nonoxide ceramics to themselves and to metals by solid-state processes and by brazing.

This book is intended for those wishing to learn more about the technology of joining of materials. It would be useful to almost anyone who is interested in or deals with joining, including designers, structural engineers, material and process engineers, manufacturing engineers, managers, and students and faculty. It is brief enough to serve as a first text on joining that can later be supplemented by more advanced texts.

I would like to acknowledge the help and guidance Eileen De Guire of ASM, the editorial staff at ASM, and the people that reviewed this manuscript for their valuable contributions.

F.C. Campbell
St. Louis, Missouri
October 2011

CHAPTER 1

Introduction to Joining

JOINING COMPRISES a large number of processes used to assemble individual parts into a larger, more complex component or assembly. The individual parts of a component meet at the *joints*. Joints transmit or distribute forces generated during service from one part to the other parts of the assembly. A joint can be either temporary or permanent. The five joint types that are predominately used in the joining of parts are the butt, tee, corner, lap, and edge joints (Fig. 1.1).

The selection of an appropriate design to join parts is based on several considerations related to both the product and the joining process. Product-related considerations include codes and standards, fitness for service, aesthetics, manufacturability, repairability, reliability, inspectability, safety, and unit cost of fabrication. Joining process considerations include material types and thicknesses, joint geometry, joint location and accessibility, handling, jigging and fixturing, distortion control, productivity, and initial and recurring manufacturing costs. Additional considerations in-

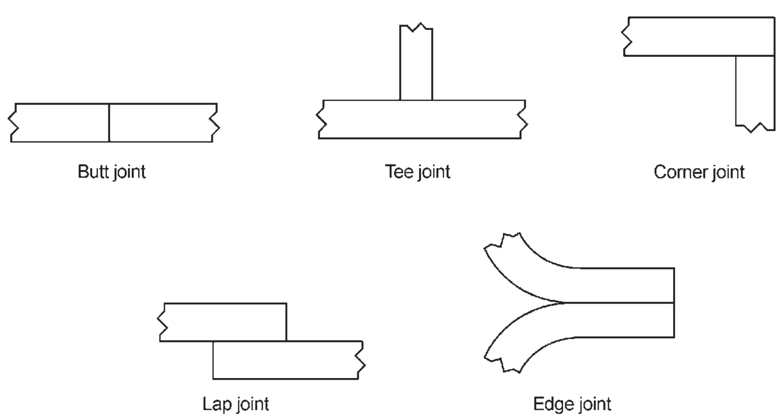


Fig. 1.1 Types of joints. Source: Ref 1.1

clude whether the joint is fabricated in a shop or at a remote site, possibilities for failure, and containment in case of a catastrophic failure (e.g., a nuclear reactor vessel).

The design or selection of appropriate joint type is determined primarily by the type of service loading the assembly will be exposed to during its service life. For example, in metallic structures, butt joints are preferred over tee, corner, lap, or edge joints for components subjected to fatigue loading, while a lap joint would be optimum for an adhesive-bonded structure. However, since high-strength adhesives are typically weak in peel, the lap joint should be loaded in shear. To effectively transfer loads through the adhesive, the substrates (or adherends) are overlapped so that the adhesive is loaded in shear. Typical adhesive-bonded joint designs are shown in Fig. 1.2. The specific joint design aspects, such as the size, length, and relative orientation of the joint, are based on stress calculations that are results of the anticipated service loads, properties of materials, properties of sections, and appropriate structural design requirements. An ideal joint is one that effectively transmits forces among the joint members and throughout the assembly, meets all structural design requirements, and can still be produced at a minimal cost. This involves selection and application of good design practices based on a thorough understanding of the available joining processes.

Assembly imposes constraints on the design. The parts must be designed so that they not only can be assembled and joined together to provide the needed function but also are easy to handle, insert, retain, and verify that they have been assembled correctly. Because assembly is an integrative process, problems with detail part designs often surface when they are assembled. For example, parts may not fit together properly, tools may not reach in the space provided, and parts may be incorrectly as-

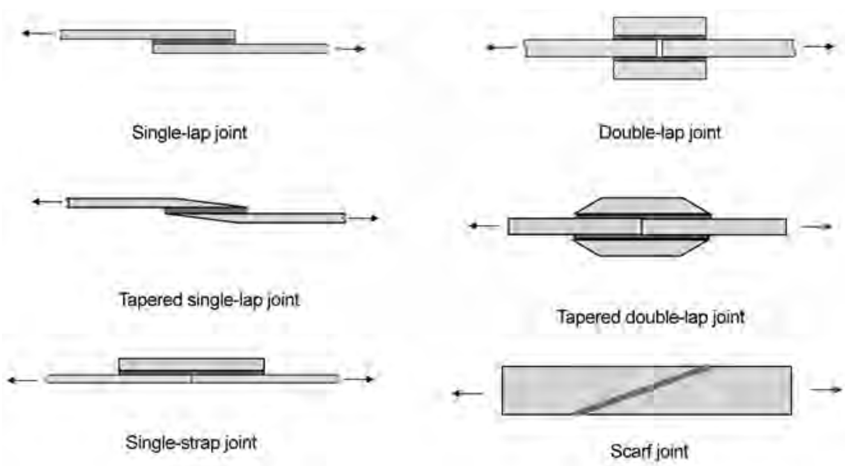


Fig. 1.2 Typical adhesive-bonded joint configurations. Note that the adhesive is loaded in shear in all configurations. Source: Ref 1.2

sembled. These problems often require extensive rework, resulting in costly schedule slippage and undesirable design compromises.

The importance of assembly as a design constraint has resulted in a greatly increased emphasis on assembly in the design process. Design and manufacturing practice now focuses on ensuring that parts conform to specifications and that variability and randomness are minimized, and on making non-value-added operations such as orienting and handling as simple and easy to perform as possible. Many product design departments now improve the ease with which products are assembled by using design for assembly (DFA) techniques, which seek to ensure ease of assembly by developing designs that are easy to assemble.

The aim of DFA is to simplify the product so that the cost of assembly is reduced. However, DFA techniques often result in improved quality and reliability, along with a reduction in production equipment and part inventory. These secondary benefits often outweigh the cost reductions in assembly.

General guidelines for DFA

- Minimize part count by incorporating multiple functions into single parts.
- Modularize multiple parts into single subassemblies.
- Assemble in open space, not in confined spaces; never bury important components.
- Make parts such that it is easy to identify how they should be oriented for insertion.
- Prefer self-locating parts.
- Standardize to reduce part variety.
- Maximize part symmetry.
- Eliminate parts that will tangle.
- Color code parts that are different but shaped similarly.
- Prevent nesting of parts; prefer stacked assemblies.
- Provide orienting features on nonsymmetries.
- Design the mating features for easy insertion.
- Provide alignment features.
- Insert new parts into an assembly from above.
- Eliminate reorientation of both parts and assemblies.
- Eliminate fasteners.
- Place fasteners away from obstructions; design in fastener access.
- Deep channels should be sufficiently wide to provide access to fastening tools; eliminate channels if possible.
- Provide flats for uniform fastening and fastening ease.
- Ensure sufficient space between fasteners and other features for a fastening tool
- Prefer easily handled parts.

Generally, a concept design is developed and then evaluated against each of these guidelines. Design modifications are then made to satisfy the guideline. There is no guarantee that a given guideline will apply to a particular design problem. Many of these guidelines are similar or the same as the rules of concurrent engineering:

Concurrent engineering rules

- Ensure that parts most likely to require maintenance are easily accessible.
- Ensure that the degree of maintenance of your product is consistent with your company's policy on making, stocking, and supplying spare parts.
- Ensure tools needed for installation and maintenance are as inexpensive and common as possible.
- The decisions made in the first 15% of a product development process fix 85% of the downstream quality and cost of the product.
- Include all experts actively.
- Resist making irreversible decisions.
- Continually optimize the designed product *and* the design process.
- Prefer concepts that are easy to manufacture.
- Prefer concepts that are easy to assemble.
- Integrate design and manufacturing.
- Do not overconstrain or underconstrain the design.
- Look ahead of the current state of the design to anticipate problems.
- Reduce the number of parts.
- Increase interchangeability of parts; standardize parts; minimize variation in parts.
- Modularize functions and subassemblies.
- Design multifunctional and multiple-use parts.
- Avoid flexible components.
- Avoid separate fasteners.
- Improve robustness.
- Allocate time/man power based on cost-benefit analysis of a proposed action.
- Maximize yield of existing equipment.
- Keep assemblies/components as independent as possible.
- Maximize tolerances.
- Test only what can be quantified; actively search for testable aspects of a design.
- Minimize machining setups and reorientations.
- Design parts for feeding and insertion into machines.
- Perform functional analysis.
- Tailor the manufacturing process to the character of the product.
- Study producibility and usability.
- Design the fabrication process.

- Design the assembly sequence for top-down assembly.
- Minimize assembly instructions.
- Use known/proven vendors and suppliers.
- Use new technologies only when necessary.
- Identify subassemblies as soon as possible in the design process.
- Do engineering changes in batches.
- Integrate quality control with assembly.
- Match assembly processes to tolerances.
- Operate on a minimum inventory.

While some of these guidelines and rules may not always be applicable, and even occasionally contradict each other, they are certainly worth considering during the design process.

1.1 Overview of Joining Processes

Joining processes include welding, brazing, soldering, mechanical fastening, and adhesive bonding (Fig. 1.2). Mechanical fastening can be used to provide either temporary or permanent joints, while adhesive bonding, welding, brazing, and soldering processes are mainly used to provide permanent joints. Mechanical fastening and adhesive bonding usually do not cause metallurgical reactions. Consequently, these methods are often preferred when joining dissimilar combinations of materials and for joining polymer-matrix composites that are sensitive to extreme heat. Welding processes are divided into two broad classes: fusion welding and solid-state welding.

1.2 Fusion Welding

Fusion welding processes involve localized melting and solidification and are normally used when joining similar material combinations or materials belonging to the same family (e.g., joining one type of stainless steel with another type). In fusion welding, the weld can be made by simply melting the edges of the two workpieces and allowing them to fuse together on cooling. This type of weld is referred to as an *autogenous weld*. The other method is to add extra material during the welding process through the melting of an electrode or filler wire during the welding process. In both cases, the welded area will have a microstructure and properties that are different from the parent metal. The three predominant zones in a fusion weld are the fusion zone, a heat-affected zone (HAZ), and the base metal as shown in Fig. 1.3. The weld deposit itself will have a cast structure of often a complex composition. Between the weld deposit and the parent metal is an HAZ that did not melt during welding but reached very high temperatures. Grain growth due to the high temperatures is commonly encountered in the HAZ.

The types of welds commonly used with fusion welding processes are shown in Fig. 1.4. Joint designs and clearances that overwhelmingly trap the beam energy within the joint cavity are preferred for increased process efficiency. When joining thick sections, the preferred joint designs allow the weld metal to freely shrink without causing cracking. In addition, multipass welding is used for thick sections to provide for full penetration. The distinctive microstructure of a multipass weld compared to a single-pass weld is shown in Fig. 1.5. To maintain tolerances, distortion due to localized heating and cooling must be prevented or controlled during welding by the use of jigs and fixtures. Residual stresses can lead to distortion after welding and are often minimized by a stress-relief anneal after welding.

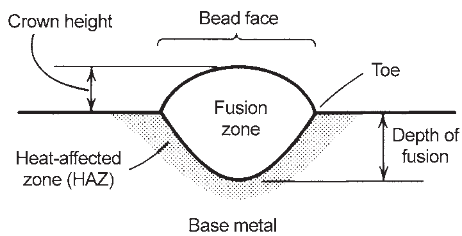


Fig. 1.3 Weld bead geometry showing fusion zone, heat-affected zone, and base metal. Source: Ref 1.3

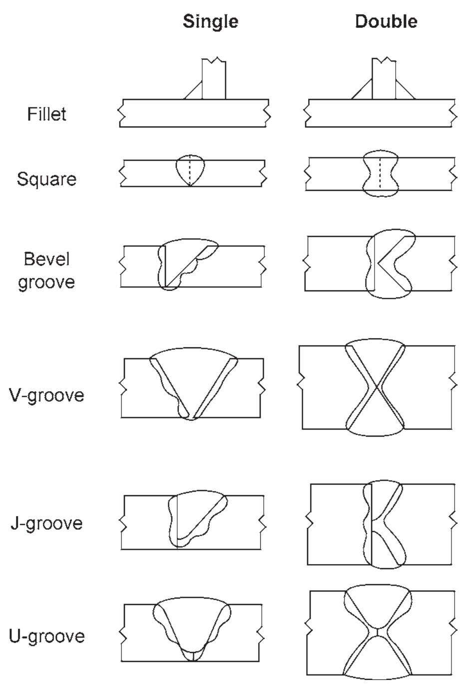


Fig. 1.4 Types of welds. Source: Ref 1.1

Thermal Welding. Heat is provided by an oxyfuel gas flame, mostly for manual welding, or by a thermit reaction for joining heavy sections such as rails. Portability is a great advantage.

Electric Arc Welding. Electric arc welding processes use electricity to produce the intense heat necessary for welding (Fig. 1.6). Some electric arc processes use a consumable electrode that melts and becomes part of the weld metal that is deposited, whereas others use a nonconsumable electrode that does not melt and does not become part of the weld deposit. Consumable electrode welding uses a filler rod as the electrode. Atmospheric protection of the molten weld metal is provided by a slag produced by the filler rod or by an externally supplied inert gas. Flux-cored wire allows a continuous and mechanized operation. The flux is supplied as a powder in submerged arc welding for horizontal welds, and a resistive slag pool protects the weld zone in electroslag welding of thick plates. Inert gas provides the protection in some welding processes, such as gas metal arc welding (GMAW) and gas tungsten arc welding (GTAW).

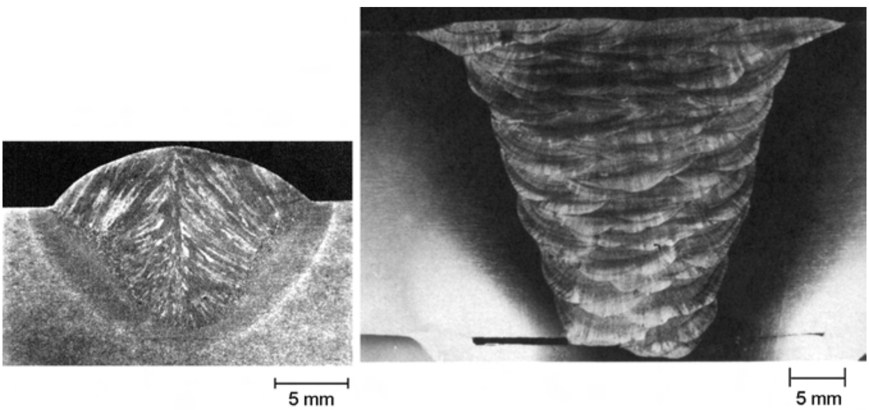


Fig. 1.5 Weld microstructures showing the fusion zone, heat-affected zone, and base metal for (a) single-pass bead-on-plate weld in A-710 steel and (b) multipass weld in 304 stainless steel. Source: Ref 1.3

Fig. 1.6 Welding using shielded metal arc welding process

Resistance Welding. After the two parts have been pressed together, electric current passes through the joint to heat and melt the interface. Pressure is kept on until solidification of the melt is complete. Spot welding is widely employed in building automotive bodies using welding robots. Seam welding, a continuous stream of spot welds, is used for making beams and box sections.

High-Energy Beam Welding. Highly concentrated beams of electrons impinge on the weld zone in electron beam (EB) welding. When the workpiece is enclosed with the gun in a vacuum chamber, a high vacuum protects the surfaces but increases cost and lowers production rates. Out-of-chamber welding is also possible. Gas (CO_2) or solid-state (Nd-YAG) lasers have seen increasing application for joining not only difficult metals and delicate parts but also sheets of different thicknesses for tailored blanks used in automobile body construction. All high-energy beam processes have the advantage that the HAZ is small, as shown in the EB weld microstructure in Fig. 1.7.

1.3 Solid-State Welding

Since solid-state welding processes do not involve melting and solidification, they are often suitable for joining not only similar but also dissimilar materials. Solid-state welding processes also have special joint design or part cross-section requirements. For example, continuous drive and inertia friction welding processes require that one of the parts exhibit a circular or near-circular cross section.

Diffusion bonding is a solid-state welding process that allows joining of a variety of structural materials, both metals and nonmetals. However, diffusion bonding requires an extremely smooth surface finish to provide intimate surface contact, a high temperature, and a high pressure, first to

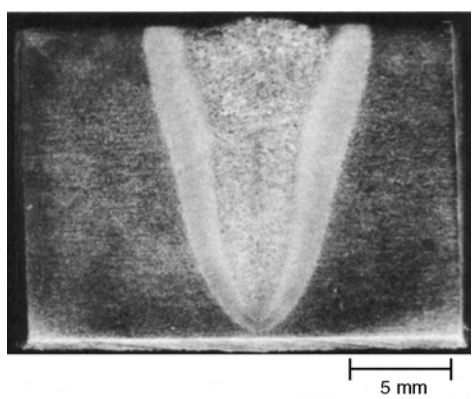


Fig. 1.7 25Cr-1Mo steel plate, single-pass electron beam weld. Macrostructure shows high depth-to-width ratio of the fusion zone, which is typical of high-energy-density welding processes. Source: Ref 1.3

allow intimate contact of the parts along the bond interface, followed by plastic deformation of the microscopic surface asperities, and then to promote diffusion across the bond interface. The need to apply pressure while maintaining part alignment imposes a severe limitation on joint design. When perfectly clean surfaces are brought into intimate contact, interatomic bonds form a joint. Bond strength is greatest when the mating metals are mutually soluble, but good bonds can be obtained with dissimilar, not otherwise weldable metals and with highly differing thicknesses. When an exceptional surface finish is difficult to achieve, a metallurgically compatible, low-melting interlayer can be inserted between the parts to produce a transient liquid phase on heating. On subsequent cooling this liquid phase undergoes progressive solidification, aided by diffusion across the solid/liquid interfaces, and thereby joins the parts. This process is similar to a brazing process.

Cold Welding. Sufficient pressure must be exerted to establish conformance of surfaces. Sliding and deformation accompanied by surface expansion are needed to break up oxides and other adsorbed films. Cold welding processes differ only in the method of providing these conditions. Complex tubular parts such as refrigerator evaporator plates can be made by depositing a parting agent in a pattern to prevent welding. After roll bonding the passages may be inflated.

Forge Welding. As a generic term, forge welding applies to bonding by deformation at the hot-working temperature. Large surface extension in hot-roll bonding creates strong bonds for cladding, as in bonding copper-nickel surface layers to a copper core for some U.S. coins.

Friction Welding. Heat is produced by friction between a rotating and stationary part; again, some melt may form that is expelled together with oxidized metal. Localization of heat allows welding of dissimilar metals and of very different dimensions (e.g., a thin stem to a large head for an internal combustion engine valve).

From a metallurgical perspective, the application of both fusion welding and solid-state welding processes must be evaluated using appropriate weldability test methods for their ability to either recreate or retain base metal characteristics across the joint. When metallurgical reactions occur, they can either benefit or adversely affect the properties of the joint. These weldability evaluations need to combine material, process, and procedure aspects to identify combinations that would provide a weld joint with an acceptable set of properties.

1.4 Brazing

Brazing is a process for joining solid metals in close proximity by introducing a liquid metal that melts above 450 °C (840 °F). A sound brazed joint generally results when an appropriate filler alloy is selected, the parent metal surfaces are clean and remain clean during heating to the flow temperature of the brazing alloy, and a suitable joint design is used that allows capillary action. Strong, uniform, leak-proof joints can be made rapidly, inexpensively, and even simultaneously. Joints that are inaccessible and parts that may not be joinable at all by other methods can often be joined by brazing. Complicated assemblies comprising thick and thin sections, odd shapes, and differing wrought and cast alloys can be turned into integral components by a single trip through a brazing furnace or a dip pot. Metal as thin as 0.01 mm (0.0004 in.) and as thick as 150 mm (6 in.) can be brazed.

Brazed joint strength is high. The nature of the interatomic (metallic) bond is such that even a simple joint, when properly designed and made, will have strength equal to or greater than that of the parent metal. The fact that brazing does not involve any substantial melting of the base metals offers several advantages over other welding processes. It is generally possible to maintain closer assembly tolerances and to produce a cosmetically neater joint without costly secondary operations. Even more important is that brazing can join dissimilar metals (or metals to ceramics) that, because of metallurgical incompatibilities, cannot be joined by traditional fusion welding processes. If the base metals do not have to be melted to be joined, it does not matter that they have widely different melting points. Therefore, steel can be brazed to copper as easily as to another steel. Brazing also generally produces less thermally induced distortion, or warping, than does fusion welding. An entire part can be brought up to the same brazing temperature, thereby preventing the kind of localized heating that causes distortion in welding.

Finally, and perhaps most important to the manufacturing engineer, brazing readily lends itself to mass production techniques. It is relatively easy to automate because the application of heat does not have to be localized, as in fusion welding, and the application of filler metal is less critical. In fact, given the proper clearance conditions and heat, a brazed joint is not dependent on operator skill, as are most fusion welding processes. Automation is also simplified by the fact that heat can be applied to the joint by many means, including torches, furnaces, induction coils, electrical resistance, and dipping. Several joints in one assembly often can be produced in one multiple-braze operation during one heating cycle, further enhancing production automation.

1.5 Soldering

Soldiering is a joining process by which two substrates are joined together using a filler metal (solder) with a liquidus ≤450 °C (≤840 °F). The substrate materials remain solid during the bonding process. The solder is usually distributed between the properly fitted surfaces of the joint by capillary action.

The bond between solder and base metal is more than adhesion or mechanical attachment, although these do contribute to bond strength. Rather, the essential feature of the soldered joint is that a metallurgical bond is produced at the interface between the filler metal and base metal. The solder reacts with the base metal surface and wets the metal by intermetallic compound formation. Upon solidification, the joint is held together by the same attraction, between adjacent atoms, that holds a piece of solid metal together. When the joint is completely solidified, diffusion between the base metal and soldered joint continues until the completed part is cooled to room temperature. Therefore, the mechanical properties of soldered joints are generally related to, but not equivalent to, the mechanical properties of the soldering alloy.

Mass soldering by wave, drag, or dip machines has been a preferred method for making high-quality, reliable connections for many decades. Correctly controlled, soldering is one of the least expensive methods for fabricating electrical connections.

1.6 Mechanical Fastening

The primary function of a fastener system is to transfer load. Many types of fasteners and fastening systems have been developed for specific requirements, such as high strength, easy maintenance, corrosion resistance, reliability at high or low temperatures, or low material and manufacturing costs. The selection and satisfactory use of a particular fastener are dictated by the design requirements and conditions under which the fastener will be used. Consideration must be given to the purpose of the fastener, the type and thickness of materials to be joined, the configuration and total thickness of the joint to be fastened, the operating environment of the installed fastener, and the type of loading to which the fastener will be subjected in service. A careful analysis of these requirements is necessary before a satisfactory fastener can be selected.

The selection of the correct fastener or fastener system may simply involve satisfying a requirement for strength (static or fatigue) or for corrosion resistance. On the other hand, selection may be dictated by a complex system of specification and qualification controls. The extent and complexity of the system needed are usually dictated by the probable cost of a fastener failure. Adequate testing is the most practical method of guarding against failure of a new fastener system for a critical application. The designer must not extrapolate existing data to a different size of the same fastener, because larger-diameter fasteners have significantly lower fatigue endurance limits than do smaller-diameter fasteners made from the same material and using the same manufacturing techniques and joint system.

Mechanical fasteners are grouped into threaded fasteners, rivets, blind fasteners, pin fasteners, special-purpose fasteners, and fasteners for composites. Rivets, pin fasteners, and special purpose fasteners are usually designed for permanent or semipermanent installation. Threaded fasteners are considered to be any threaded part that, after assembly of the joint, may be removed without damage to the fastener or to the members being joined. Rivets are permanent one-piece fasteners that are installed by mechanically upsetting one end. Blind fasteners are usually multiple-piece devices that can be installed in a joint that is accessible from only one side. When a blind fastener is being installed, a self-contained mechanism, an explosive, or other device forms an upset on the inaccessible side. Pin fasteners are one-piece fasteners, either solid or tubular, that are used in assemblies in which the load is primarily shear. A malleable collar is sometimes swaged or formed on the pin to secure the joint. Special-purpose fasteners, many of which are proprietary, such as retaining rings, latches, slotted springs, and studs, are designed to allow easy, quick removal and replacement and show little or no deterioration with repeated use.

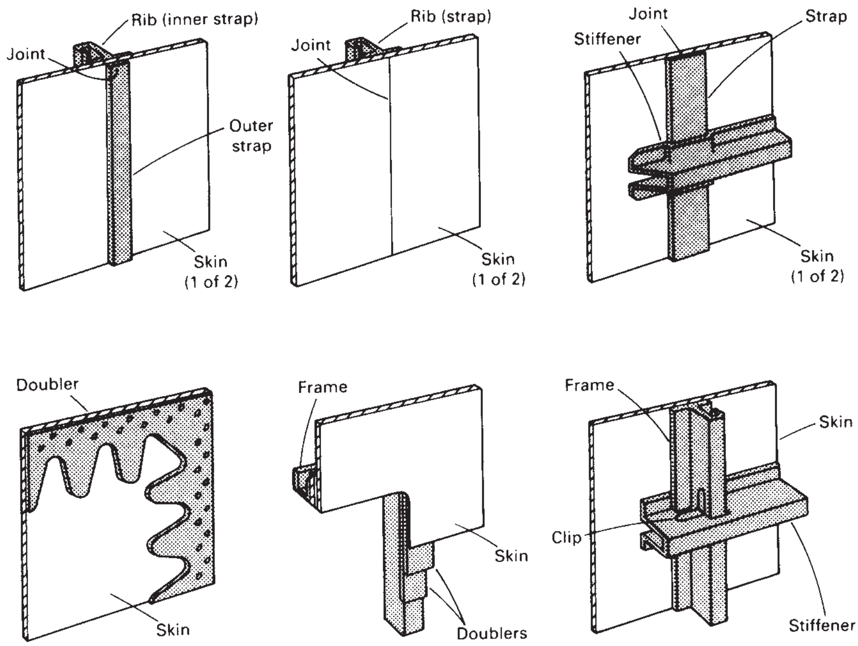
1.7 Adhesive Bonding

Adhesive bonding is a materials joining process in which an adhesive (usually a thermosetting or thermoplastic resin) is placed between the faying surfaces of the parts or bodies called adherends. The adhesive then solidifies or hardens by physical or chemical property changes to produce a bonded joint with useful strength between the adherends.

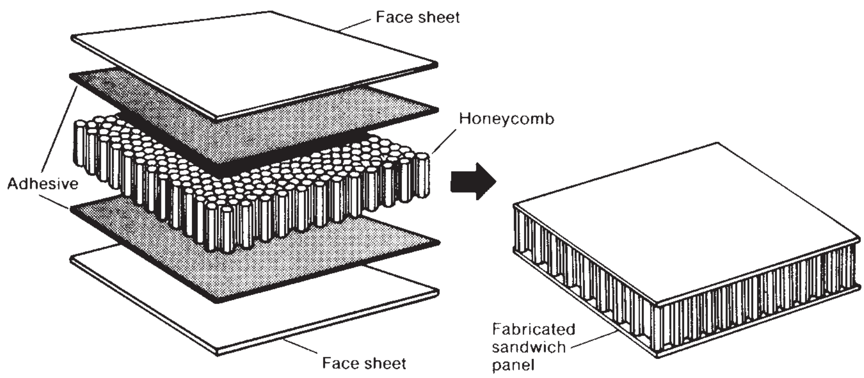
Adhesive-bonded joints are used extensively in aircraft components and assemblies where structural integrity is critical. The structural components are not limited to aircraft applications; they can be translated to commercial and consumer product applications as well. Adhesive bonding is very competitive compared with other joining methods in terms of production cost, ability to accommodate manufacturing tolerances and component complexity, facility and tooling requirements, reliability, and repairability,

Some typical aircraft applications for adhesive bonded structures include:

- Metal-to-metal bonded structures that are locally reinforced by bonded doubler plates or some other type of reinforcement (Fig. 1.8a)
- Metal-to-metal bonded multiple laminations where each layer progressively increases the cross-sectional area of the component (e.g., for stringers and spar caps)
- Bonded joints between rather thin metal sheet and a low-density core material, called honeycomb or sandwich structures (Fig. 1.8b). Core materials include paper dipped in a phenolic resin, fiberglass, aluminum alloy foil, Nomex (aramid fiber paper dipped in phenolic resin), graphite-reinforced plastic, and Kevlar fabric



(a) Adhesive bond joint configurations



(b) Honeycomb bonded assembly

Fig. 1.8 Examples of (a) adhesive bond joint configurations and (b) honeycomb bonded assembly. Source: Ref 1.4

Aluminum alloys that are commonly adhesive bonded include 2024 (T3, T6, and T86), 3*xxx* series alloys, 5052-H39, 5056-H39, and 7075-T6. These alloys may be bonded to themselves, each other, other metals, and many nonmetals, including all forms of paper products, insulation board, wood-particle board, plaster board, plywood, fiberglass, and various polymers and organic matrix composites. Other metals commonly joined by adhesive bonding include Ti-6Al-4V, copper and copper alloys used in microelectronic applications, low-carbon steels, and stainless steels. Successful adhesive bonding of all of these metals requires stringent cleaning procedures, and the cleaned surfaces must be protected from contamination until they are bonded.

Because an adhesive can transmit loads from one member of a joint to another, it allows a more uniform stress distribution than is obtained using mechanical fasteners. Thus, adhesives often permit the fabrication of structures that are mechanically equivalent or superior to conventional assemblies and have cost and weight benefits. For example, adhesives can join thin metal sections to thick sections so that the full strength of the thin section is used. In addition, adhesives can produce joints with high strength, rigidity, and dimensional precision in the light metals, such as aluminum, that may be weakened or distorted by welding.

Because the adhesive in a properly prepared joint provides full contact with mating surfaces, it forms a barrier so that fluids do not attack or soften it. An adhesive may also function as an electrical and/or thermal insulator in a joint. Its thermal insulating efficiency can be increased, if necessary, by forming an adhesive with the appropriate cell structure in place. On the other hand, electrical and thermal conductivity can be raised appreciably by adding metallic fillers. Oxide fillers, such as alumina, increase only thermal conductivity. Electrically conductive adhesives, filled with silver flake, are available with specific resistivities <50 times that of bulk silver.

Adhesives can also prevent electrochemical corrosion in joints between dissimilar metals. They may also act as vibration dampers. The mechanical damping characteristics of an adhesive can be changed by formulation. However, changing such a property in an adhesive generally changes other properties of the joint, such as tensile or shear strength, elongation, or resistance to peel or cleavage. A property somewhat related to the ability to damp vibration is resistance to fatigue. A properly selected adhesive can generally withstand repeated strains induced by cyclic loading without the propagation of failure-producing cracks.

Adhesives usually do not change the contours of the parts they join. Unlike screws, rivets, or bolts, adhesives give little or no visible external evidence of their presence. They are used to join skins to airframes, and they permit the manufacture of airfoils, fuselages, stabilizers, and control surfaces that are smoother than similar conventionally joined structures and that consequently have better aerodynamic efficiency. These structures also have greater load-bearing capability and higher resistance to fatigue than conventionally joined structures.

1.8 Joint Design Considerations

When designing a joint, one should initially consider manufacturability of the joint, whether at a shop or at a remote site. For example, consider the need for a high-integrity, high-performance joint between two dissimilar materials such as a low-carbon steel and an aluminum alloy. If this joint has to be produced at a remote site, the available choice of joining processes is extremely limited. A viable alternative would be to produce at a shop a transition piece involving the two dissimilar materials. Using controlled process conditions at a shop, one could produce a high-integrity transition piece using one of the solid-state welding processes. The selection of the appropriate solid-state welding process would depend on joint (part) geometry. A transition joint between a plate and a pipe is best produced using a friction welding process, whereas a joint between two large plate surfaces is best produced using explosive bonding. Because these joining processes do not involve melting and solidification, they provide high-integrity joints free from porosity or solidification-related defects. Transition pieces so produced could be used at a remote site to make similar metal joints between component parts with no undue quality assurance or quality control concerns.

A joint must be designed to benefit from the inherent advantages of the selected method of joining. For example, braze joints perform very well when subjected to shear loading but not when subjected to pure tensile loading. When using a brazing process to join parts, it would be beneficial to employ innovative design features that would convert a joint subjected to tensile loading to shear loading. For example, the use of single- or double-lap joints (Fig. 1.2) instead of butt joints can provide a beneficial effect in flat parts and tubular sections. Joints should also be designed to reduce stress concentrations. Sharp changes in part geometry near the joint tend to increase stress concentration or notch effects. Smooth contours and radiused corners tend to reduce stress concentration effects. A number of ways to redistribute stresses in a brazed joint are shown in Fig. 1.9.

When determining appropriate joint designs, one should initially consider standard or recommended joint designs. In practice, several standard joint designs may be suitable for producing a joint. Subtle or innovative features could be added to the recommended joint designs to improve productivity through mechanization or automation, to enhance joint performance, and to ensure safety.

Orientation and Alignment. Design features that promote self-location and maintain the relative orientation and alignment of component parts save valuable time during fit-up and enhance the ability to produce a high-quality joint. For example, operations involving furnace brazing or diffusion bonding with interlayers benefit from such a type of joint design, because they allow preplacement of the brazing filler or the interlayer in the joint. The pin-socket type of temporary joints in modern electrical, telephone, and computer connectors allow temporary joining of cables in only one way. These joint designs strongly discourage any inadvertent misalignment or wrong orientation of the connectors and thereby eliminate a variety of hazards. The snap-on interlocking features in twisted, threaded, or nonthreaded adapter joint designs, commonly used in chil-

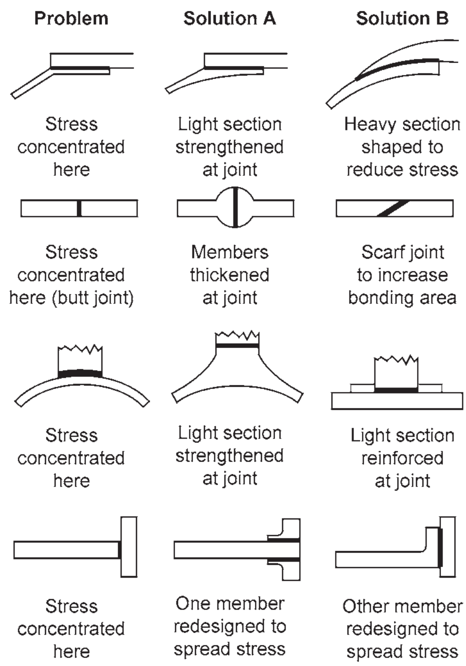


Fig. 1.9 Design of a brazed joint to redistribute stress. Source: Ref 1.1

dren's toys, often allow the snapping sound of a latch to indicate the satisfactory completion of the joint and its safety for the intended use.

Jigging and fixturing can also be used to maintain relative orientation of parts. When necessary, the fixturing devices should be designed for the least possible thermal mass and pinpoint or knife-line contact with the parts. Fixtures of low thermal mass and minimal contact with the parts reduce the overall thermal load during joining. Further, arc welding processes generally allow higher deposition rates when joining is performed in the flat position, where gravity effects tend to support a large volume of molten weld metal at the joint region. When joining parts that exhibit a nonplanar joint contour, positioning equipment can be used to continuously manipulate the parts so that the welding is performed in the flat position. In such cases, the design of the joint and fixtures should be complementary to the positioning equipment used, and it should not interfere with the functioning of the positioning equipment.

Joint Location and Accessibility. From a structural integrity standpoint, joint locations should be chosen such that they are not in regions subjected to maximum stress. Concurrently, joints must be placed in locations that will allow operators to readily make the joints using the selected method of joining. The effect of joint location on accessibility is illustrated in Fig. 1.10. Limited accessibility can reduce the overall quality of the joint, decrease productivity, or both. Invariably, limited accessibility to

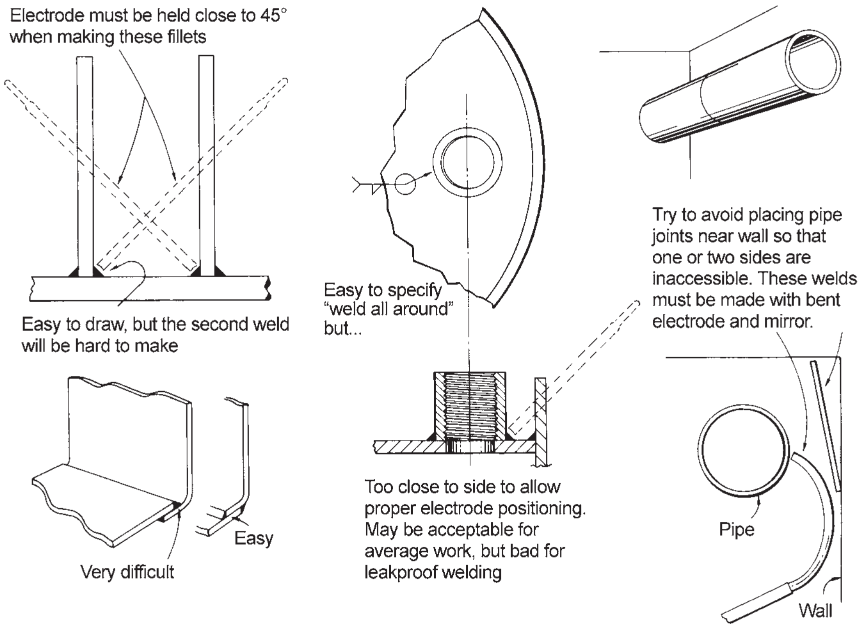


Fig. 1.10 Effect of joint location on accessibility. Source: Ref 1.4

produce joints also limits accessibility to perform nondestructive evaluation of joint quality, either during the time the joint is made or afterward.

Weld joint designs employ bevel angles and root openings to enhance accessibility to the welding torch (or electrode) and provide adequate weld penetration. The best bevel angles provide adequate accessibility while reducing the amount of weld metal required to complete the joint. Currently, computer-based software tools are available to facilitate the selection of a weld joint for minimizing the amount of weld metal. Use of such computer-based selection of joint designs increases welding productivity (joint completion rate), improves quality, and reduces overall fabrication cost, but such designs must be used only when they are consistent with structural design requirements. For this reason, codes such as the ASME Boiler and Pressure Vessel Code, Section IX: Welding and Brazing Qualifications, and ANSI/AWS D1.1 Structural Welding Code Steel provide flexibility to a welding manufacturer (fabricator) to select or change weld joint design for fabrication, but they require the manufacturer to qualify the welding procedure to meet design performance requirements whenever changes are made to a previously qualified, nonstandard weld joint design. In recent years, the use of narrow-gap gas metal arc welding (GMAW) and submerged arc welding techniques in the place of conventional welding techniques for welding thick-section pressure vessel steels has contributed significantly to increased weld joint completion rates.

Unequal Section Thickness. When constituent members of an assembly exhibit unequal section thicknesses, modifications to the recommended joint designs will be necessary for a variety of technical reasons, but mainly to provide a smooth flow of stress patterns through the unequal sections. When making a fillet weld using an arc welding process, if thicknesses of the members are not greatly different, directing the arc toward the thicker member may produce acceptable penetration. However, special designs for joining will be required when the components to be welded exhibit a large heat sink differential (difference in heat-dissipating capacities). When a thick member is joined to a thin member, the welding heat input needed to obtain a good penetration into the thick member is sometimes too much for the thin member and results in undercutting of the thin member and a poor weld. Similarly, if the proper amount of heat for the thin member is used, the heat is insufficient to provide adequate fusion in the thick member, and again, a poor weld results. Too little heat input can also cause underbead cracking in certain structural materials.

A widely applicable method of minimizing heat sink differential is to place a copper backing block against the thin member during fusion welding (Fig. 1.11). The block serves as a chill, or heat sink, for the thin member. The block can be beveled along one edge so that it can be used when horizontal fillet welds are deposited on both sides of a thin member. Copper backing bars or strips are made in a variety of shapes and sizes to dissipate heat as needed. Often some experimentation and proof testing are required to obtain the optimum backing location and design. Another way to obtain equalized heating and smooth transfer of stress where unequal section thicknesses are being welded is to taper one or both members to obtain an equal width or thickness at the joint. Commonly, when two pipes of dissimilar internal diameter and wall thickness are to be joined, a convenient way is to introduce a "reducer" between the two pipes. One end of the reducer will have the same size and wall thickness as the larger pipe, while the other end of the reducer will have the same size and wall thickness as the smaller pipe.

Distortion Control. Design of an appropriate weld joint can also help reduce welding-related distortion. Fusion welding processes employ lo-

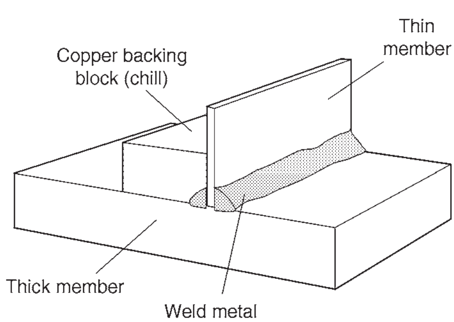


Fig. 1.11 Use of copper backing block as a chill to minimize heat sink differentials. Source: Ref 1.4

calized melting and solidification to join component parts, which can result in excessive thermal strains. These thermal strains depend on the type of material, the welding process, and the welding procedure. Thermal strains produced by fusion welding processes can cause residual stresses and distortion, leading to transverse and angular shrinkage. Reducing the overall length of the weld or the amount of weld metal that needs to be deposited to complete a joint reduces both residual stresses and distortion. For example, intermittent welding instead of continuous welding reduces the overall length of a weld. Similarly, the use of a double-V groove instead of a single-V groove results in the reduction of the amount of weld metal and minimizes transverse shrinkage. Further, the amount of angular shrinkage is strongly influenced by the ratio of the weld metal in the top and the bottom sides of the plate. To minimize the out-of-plane distortion in fillet welded joints, efforts should be directed to using the minimum size of the welds that is consistent with strength considerations.

1.9 Process Selection for Joining

Frequently, several joining processes can be used for a particular job. The major problem is to select the one that is the most suitable in terms of fitness for service and cost. These two factors, however, may not be totally compatible, thus forcing a compromise. Selection of a process can depend on a number of considerations, including the number of components being fabricated, capital equipment costs, joint location, structural mass, and desired performance of the product. The adaptability of the process to the location of the operation or the type of shop, and the experience and abilities of the employees may also have an impact on the final selection.

General guides for selecting a suitable joining process for different types of applications are given in Tables 1.1 and 1.2. These tables should be regarded as only general guidance. Additional resources should be consulted for specific applications before final decisions are made or recommended.

Table 1.1 Comparison of joining process characteristics

Attribute	Welding	Brazing and soldering	Mechanical fastening	Adhesive bonding
Performance	Permanent joints	Usually permanent (soldering may be nonpermanent)	Threaded fasteners permit disassembly	Permanent joints
Stress distribution	Local stress points in structure	Fairly good stress distribution	Points of high stress at fasteners	Good uniform load distribution over joint area (except in peel)
Appearance	Joint appearance usually acceptable. Some dressing necessary for smooth surfaces	Good joint appearance	Surface discontinuities sometimes unacceptable	No surface marking. Joint almost invisible

(continued)

Abbreviations: CTE, coefficient of thermal expansion; NDT, nondestructive testing. Source: Ref 1.5

Table 1.1 (continued)

Attribute	Welding	Brazing and soldering	Mechanical fastening	Adhesive bonding
Materials joined	Generally limited to similar material groups	Some capability for joining dissimilar materials	Most forms and materials can be fastened	Ideal for joining most dissimilar materials. CTE difference a concern for elevated temperature bonds
Temperature resistance	Very high temperature resistance	Temperature resistance limited by filler metal	High temperature resistance	Poor resistance to elevated temperatures
Mechanical resistance	Special provisions often necessary to enhance fatigue resistance	Fairly good resistance to vibration	Special provisions for fatigue and resistance to loosening at joints	Excellent fatigue properties. Electrical isolation reduces corrosion.
Joint preparation	Little or none on thin material. Edge preparation for thick plates	Prefluxing usually required	Hole preparation and tapping for threaded fasteners	Stringent cleaning required
Postprocessing	Heat treatment sometimes necessary	Corrosive fluxes must be cleaned off	Usually none. Occasionally retightening in service	Not usually required
Equipment	Relatively expensive, bulky, heavy power supply often required	Manual equipment cheap. Special furnaces and automatic equipment expensive	Relatively cheap and portable for manual assembly. Automated equipment can be expensive.	Can be relatively cheap or expensive for tooling and presses or autoclaves
Consumables	Wire, rods fairly cheap	Some braze alloys expensive. Soft solders cheap	Quite expensive	Structural adhesives somewhat expensive
Production rate	Can be very fast	Automatic processes quite fast	Manual processes slow. Automated processes can be very fast.	Seconds to hours depending on type
Quality assurance	Nondestructive testing (NDT) methods well established	NDT for brazed joints established. Solder inspection can be difficult.	Reasonable confidence in torque control tightening	NDT methods limited

Abbreviations: CTE, coefficient of thermal expansion; NDT, nondestructive testing. Source: Ref 1.5

Table 1.2 Recommended joining processes for various metal groups

Material	Thickness(a)	Shielded metal arc welding	Submerged arc welding	Gas metal arc welding	Flux-cored arc welding	Gas tungsten arc welding	Plasma arc welding	Electroslag welding	Electrogas welding	Resistance welding	Flash welding	Oxyfuel welding	Diffusion welding	Friction welding	Electron beam welding	Laser beam welding	Torch brazing	Furnace brazing	Induction brazing	Resistance brazing	Dip brazing	Infrared brazing	Diffusion brazing	Soldering
Carbon steel	S	X	X	X		X				X	X	X			X	X	X	X	X	X	X	X	X	X
	I	X	X	X	X	X				X	X	X		X	X	X	X	X	X	X	X		X	X
	M	X	X	X	X					X	X	X		X	X	X	X	X	X				X	
	T	X	X	X	X			X	X		X	X		X	X			X					X	
Low-alloy steel	S	X	X	X		X				X	X	X	X		X	X	X	X	X	X	X	X	X	X
	I	X	X	X	X	X				X	X		X	X	X	X	X	X	X				X	X
	M	X	X	X	X						X		X	X	X	X	X	X	X				X	
	T	X	X	X	X			X		X	X		X	X	X		X							
Stainless steel	S	X	X	X		X	X			X	X	X	X		X	X	X	X	X	X	X	X	X	X
	I	X	X	X	X	X	X			X	X		X	X	X	X	X	X	X				X	X
	M	X	X	X	X		X				X		X	X	X	X	X	X	X				X	
	T	X	X	X	X			X			X		X	X	X			X					X	

(continued)

(a) S, sheet, up to 3 mm (⅛ in.); I, intermediate, 3 to 6 mm (⅛ to ¼ in.); M, medium, 6 to 19 mm (¼ to ¾ in.); T, thick, 19 mm (¾ in.) and up. Source: Ref 1.4

Table 1.2 (continued)

Material	Thickness(a)	Shielded metal arc welding	Submerged arc welding	Gas metal arc welding	Flux-cored arc welding	Gas tungsten arc welding	Plasma arc welding	Electroslag welding	Electrogas welding	Resistance welding	Flash welding	Oxyfuel welding	Diffusion welding	Friction welding	Electron beam welding	Laser beam welding	Torch brazing	Furnace brazing	Induction brazing	Resistance brazing	Dip brazing	Infrared brazing	Diffusion brazing	Soldering
Cast iron	I	X										X					X	X	X				X	X
	M	X	X	X	X							X					X	X	X				X	X
	T	X	X	X	X							X						X					X	
Nickel and alloys	S	X		X		X	X			X	X	X			X	X	X	X	X	X	X	X	X	X
	I	X	X	X		X	X			X	X			X	X	X	X	X	X				X	X
	M	X	X	X			X				X			X	X	X	X	X					X	
	T	X		X				X			X			X	X			X					X	
Aluminum and alloys	S	X		X		X	X			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	I	X		X		X				X	X		X	X	X	X	X	X			X		X	X
	M	X		X		X					X			X	X		X	X			X		X	
	T	X		X				X	X		X				X			X					X	
Titanium and alloys	S			X		X	X			X	X		X		X	X		X	X			X	X	
	I			X		X	X				X		X	X	X	X		X					X	
	M			X		X	X				X		X	X	X	X		X					X	
	T			X							X		X		X		X	X					X	
Copper and alloys	S			X		X	X				X				X		X	X	X	X			X	X
	I			X			X				X			X	X		X	X		X			X	X
	M			X							X			X	X		X	X					X	
	T			X							X				X			X					X	
Magnesium and alloys	S			X		X				X					X	X	X	X			X		X	
	I			X		X				X	X			X	X	X	X	X			X		X	
	M			X							X			X	X	X		X					X	
	T			X							X				X									
Refractory alloys	S			X		X	X			X	X				X		X	X	X	X		X	X	
	I			X			X				X				X		X	X					X	
	M									X	X													
	T																							

(a) S, sheet, up to 3 mm (⅛ in.); I, intermediate, 3 to 6 mm (⅛ to ¼ in.); M, medium, 6 to 19 mm (¼ to ¾ in.); T, thick, 19 mm (¾ in.) and up. Source: Ref 1.4

ACKNOWLEDGMENTS

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Joining—Understanding the Basics
F.C. Campbell, editor

CHAPTER 2

Arc Welding of Metals

FUSION WELDING PROCESSES involve localized melting and solidification and are normally used when joining similar material combinations or materials belonging to the same family (e.g., joining one type of stainless steel with another type). Fusion welding methods include arc welding processes, resistance welding processes, and other methods such as oxyfuel welding, electron beam welding, and laser beam welding. Figure 2.1 compares these five process variations in terms of their productivity versus the relative cost of equipment.

The term *arc welding* applies to a large and diversified group of welding processes that use an electric arc as the source of heat to melt and join

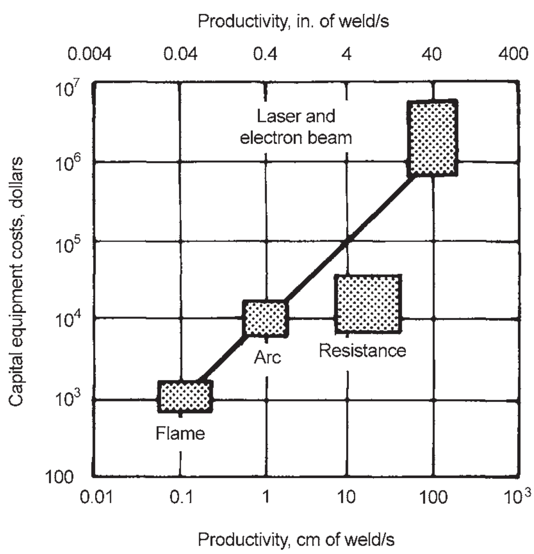

Fig. 2.1 Approximate relationship between capital cost of welding equipment and speed at which sheet metal joints can be produced, for five welding process variations. Source: Ref 2.1

metals. The formation of a weld between metals that are arc welded may or may not require the use of a filler metal. The welding arc is struck between the workpiece and the tip of an electrode. The electrode will be either a consumable wire or rod or a nonconsumable carbon or tungsten rod that carries the welding current. The electrode is manually or mechanically moved along the joint, or it remains stationary while the workpiece is moved. When a nonconsumable electrode is used, filler metal can be supplied by a separate rod or wire if needed. A consumable electrode, however, will not only conduct the current that sustains the arc but also melt and supply filler metal to the joint. Arc welding processes use shielding gases, slag coverings, or both to protect the hot weld metal from oxidation.

Shielding gases are used to protect the molten metal from atmospheric nitrogen and oxygen as the weld pool is being formed. The shielding gas also promotes a stable arc and uniform metal transfer. In gas metal arc welding (GMAW) and flux cored arc welding (FCAW), the gas used has a substantial influence on the form of metal transfer during welding. This, in turn, affects the efficiency, quality, and overall operator acceptance of the welding operation. The shielding gas interacts with the base material and with the filler material, if any, to produce the basic strength, toughness, and corrosion resistance of the weld. It can also affect the weld bead shape and the penetration pattern.

The basic characteristics of gases used for shielding during arc welding are (Ref 2.2):

Argon is inert or unreactive with respect to the materials present in the welding electrode. With its low ionization potential, argon promotes easy arc starting and stable arc operation. Its lower thermal conductivity promotes the development of axial "spray" transfer in certain forms of GMAW. It is also used in applications where base material distortion must be controlled or where good gap-bridging ability is required.

Helium, unlike argon, is lighter than air and has a low density. Like argon, it is chemically inert and does not react with other elements or compounds. Because of its high thermal conductivity and high ionization potential, more heat is transferred to the base material, thus enhancing the penetration characteristics of the arc. In many applications, it also allows higher weld travel speeds to be obtained. Because of its higher cost, helium is frequently combined with argon or argon mixtures to enhance the overall performance of the blend while minimizing its cost.

Oxygen combines with almost all known elements except rare and inert gases; it vigorously supports combustion. Small amounts of oxygen are added to some inert mixtures to improve the stability of the welding arc developed as well as to increase the fluidity of the weld puddle. In the spray-transfer mode of GMAW, small additions of oxygen enhance the range over which this spatterless form of welding can be performed. The droplet size decreases and the number of drops transferred per unit time increases as oxygen is added to the blend.

Carbon dioxide (CO_2) is a reactive gas that is commonly used alone in certain types of GMAW. Oxidation of the base material and any filler electrode occurs readily. Carbon dioxide is added to argon blends to improve are stability, enhance penetration, and improve weld puddle flow characteristics. The higher thermal conductivity of CO_2 (because of the dissociation and recombination of its component parts) transfers more heat to the base material than does argon alone. A broader penetration pattern versus argon is obtained; however, base material distortion and lack of gap-bridging ability are possible problems.

Hydrogen is the lightest known element and is a flammable gas. Explosive mixtures can be formed when certain concentration of hydrogen are mixed with oxygen or air. It is added to inert gases to increase the heat input to the base material or for operations involving cutting and gouging. Because some materials are especially sensitive to hydrogen-related contamination, its use is generally limited to special applications, such as the joining of stainless steels, and to plasma arc cutting and gouging.

Nitrogen is generally considered to be inert except at high temperatures. At arc welding temperatures, it will react with some metals (e.g., aluminum, magnesium, steel, and titanium), so it is not used as a primary shielding gas. It can be used with other gases for some welding applications (e.g., copper) and is also widely used in plasma cutting.

To obtain a shielding gas that is suited to a specific application, a mix of gases is generally needed. Each basic gas contributes certain characteristics to the performance of the overall mix. Some gas blends have relatively specific areas of application and limited operating ranges; others can be used on many materials under a variety of welding conditions. Each component of the blend brings with it properties that are supplemented by the others to produce an enhanced level of performance.

Fluxes are used to improve arc stability, to provide a slag, to add alloying elements, and to refine the weld pool. The desirable properties of a flux are:

- Stabilize arc and control arc resistivity
- Provide slag with the proper melting temperature
- Provide a low-density slag
- Permit use of different types of current and polarity
- Add alloying elements
- Refine the weld pool by deoxidation and desulfurization
- Provide proper viscosity for out-of-position welding
- Promote slag detachability
- Produce a smooth weld contour
- Reduce spatter and fume

The slag that forms during welding covers the hot weld metal and protects it from the atmosphere. Welding slag consists of the glass-forming components of the flux, as well as inclusions that form in the weld pool, coalesce, rise, and become incorporated into the slag. Silicates, aluminates, and titanates are all primary slag formers. Slag must solidify on the already solidified weld deposit to protect the surface from oxidation during cooling. Specific physical properties are required of the slag. It must melt below the melting temperature of steel (~1450 °C, or 2640 °F), must have a density significantly less than that of steel to reduce slag entrapment in the weld deposit, must possess the proper viscosity in the temperature range of 1450 to 1550 °C (2640 to 2820 °F), and must easily detach from the weld deposit after welding. Alloying is achieved by powder metal additions to the flux coating. Manganese, silicon, chromium, niobium, and other alloying additions are adjusted in the weld pool by ferroalloy powder additions. Specially prepared alloy additions of Fe-50Si, Fe-80Mn, Fe-60Mn-30Si, and others are used.

It is estimated that 90% of all industrial welding is done by arc welding. Specific arc welding methods include:

- Shielded metal arc welding (SMAW)
- Flux cored arc welding (FCAW)
- Submerged arc welding
- Gas metal arc welding (GMAW), which is also commonly referred to as MIG (metal inert gas) welding
- Gas tungsten arc welding (GTAW), which is also commonly referred to as TIG (tungsten inert gas) welding
- Plasma arc welding (PAW)
- Plasma-GMAW welding
- Electroslag welding and electrogas welding

2.1 Shielded Metal Arc Welding

The shielded metal arc welding (SMAW) process is the most widely used arc welding process. It is the simplest in terms of equipment requirements, but it is perhaps the most difficult in terms of welder training and skill-level requirements. Although welder skill level is a concern, most welders entering the field start as “stick welders” and develop the necessary skills through training and experience. The equipment investment is relatively small, and welding electrodes (except for the very reactive metals, e.g., titanium and magnesium) are available for virtually all manufacturing, construction, or maintenance applications. Shielded metal arc welding has the greatest flexibility of all the welding processes, because it can be used in all positions (flat, vertical, horizontal, and overhead), with virtually all base metal thicknesses (≥1.6 mm, or 1/16 in.), and in areas of limited accessibility, which is a very important capability.

Shield metal arc welding is a manual arc welding process in which the heat for welding is generated by an arc established between a flux-covered consumable electrode and a workpiece. The electrode tip, molten weld pool, arc, and adjacent areas of the workpiece are protected from atmospheric contamination by a gaseous shield obtained from the combustion and decomposition of the electrode covering. Additional shielding is provided for the molten metal in the weld pool by a covering of molten flux or slag. Filler metal is supplied by the core of the consumable electrode and from metal power mixed with the electrode coverings of certain electrodes. Shielded metal arc welding is often referred to as arc welding with stick electrodes, manual metal arc welding, and stick welding.

Shielded metal arc welding is the most widely used welding process for joining metal parts because of its versatility and its less complex, more portable, and less costly equipment. Shielded metal arc welding can be done indoors or outdoors. Joints in any position that can be reached with an electrode (i.e., overhead joints and vertical joints) can be welded. By the use of bent electrodes, joints in blind areas can be welded, including the back sides of pipes in restricted areas, which are inaccessible for most welding processes. The power-supply leads can be extended for relatively long distances, and no hoses are required for shielding gas or water cooling.

The base metal thicknesses that can be welded using the SMAW process generally range from 1.6 mm (1/16 in.) to an unlimited thickness. The thinner materials require a skilled welder, tight fit-up, and the proper small-diameter welding electrode. Welding position also is important when determining the minimum plate thicknesses that can be welded. Flat-position butt welds and horizontal fillet welds are generally considered the easiest to weld. Out-of-position welding (vertical, overhead) requires greater skill.

Although the SMAW process finds wide application for welding virtually all steels and many of the nonferrous alloys, it is primarily used to join steels, including low-carbon or mild steels, low-alloy steels, high-strength steels, quenched-and-tempered steels, high-alloy steels, stainless steels, and many of the cast irons. The SMAW process is also used to join nickel and its alloys and, to a lesser degree, copper and its alloys. It can be, but rarely is, used for welding aluminum. In addition to joining metals, the SMAW process is frequently used for the protective surfacing of base metals. The surfacing deposit can be applied for the purpose of corrosion control or wear resistance (hardfacing).

An adequate power supply is required for SMAW. Suitable cables are used to attach one terminal of the power supply to the electrode holder and the other terminal to a ground clamp (Fig. 2.2). To start welding, an arc is struck by briefly touching the workpiece with the tip of the electrode. The welder guides the electrode by hand and controls its position, direction, travel speed, and arc length (the distance between the end of the electrode

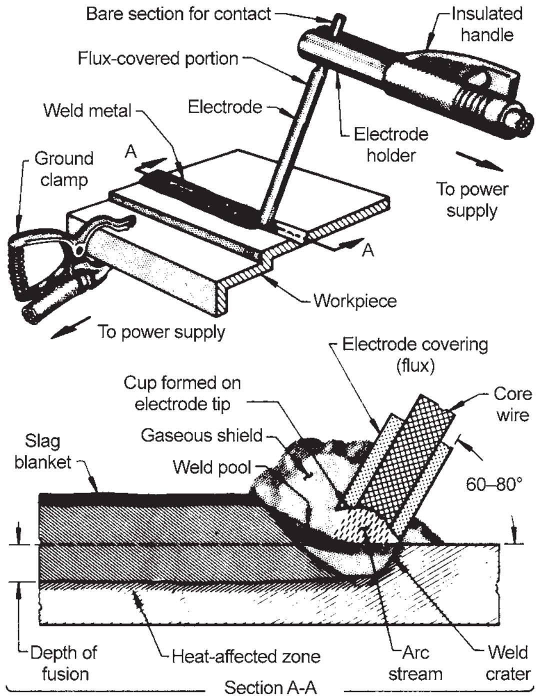

Fig. 2.2 Setup and fundamentals of operation for shielded metal arc welding. Source: 2.3

and the work surface). In many applications in which electrodes with heavy coverings are used, the welder actually drags the electrode in the joint or on the work and uses the electrode angle to control arc length.

The circuit diagram for the SMAW process is shown in Fig. 2.3(a). The equipment consists of a power source, electrode holder, and welding cables that connect the power source to the electrode holder and the workpiece. The different modes of electric arc heating are also illustrated (Fig. 2.3b). If the potential difference or voltage of the power supply is unchanging in polarity (i.e., the cathode remains the cathode and the anode remains the anode at all times that current is flowing), the electricity is said to be operating as "direct current" or dc mode. If the polarity is cycled back and forth, the electricity is said to be operating as "alternating current" or ac mode. With dc operation, the workpiece can be either positive or negative relative to the electrode in the welding source. The two modes of dc operation are typically referred to as:

- *Direct current straight polarity (DCSP)* refers to arc heating when the workpiece is positive and the welding electrode is negative. This operating mode also is called dc electrode negative (DCEN or DC–)
- *Direct current reverse polarity (DCRP)* refers to arc heating when the workpiece is negative and the welding electrode is positive. This operating mode also is called dc electrode positive (DCEP or DC+)

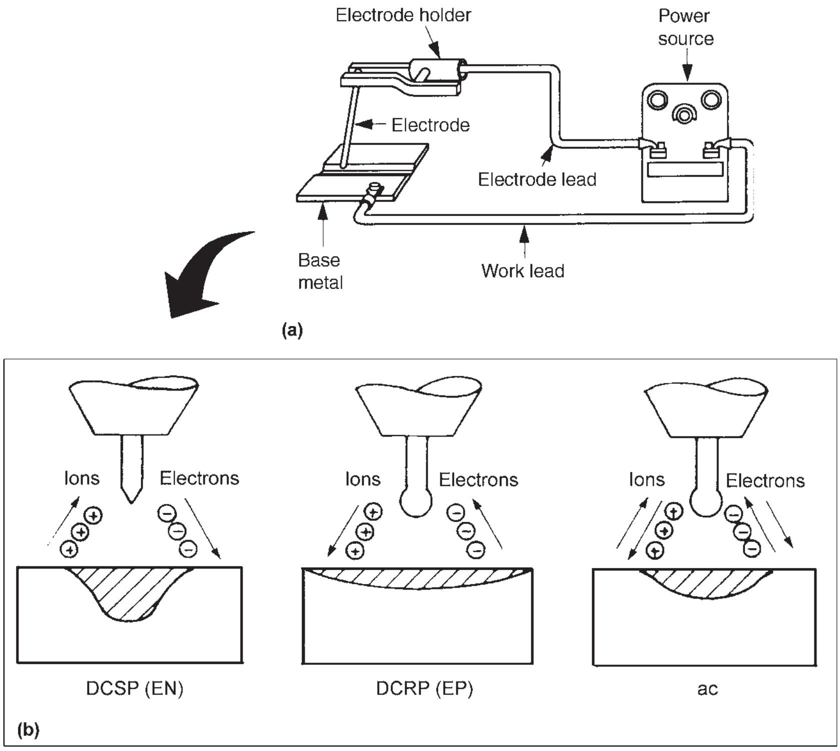

Fig. 2.3 (a) Shielded metal arc circuit diagram. (b) Polarity configurations for electric arc welding. DCSP (EN): direct current, straight polarity electrode negative); DCRP (EP): direct current, reverse polarity (electrode positive); AC: alternating current; W: welding electrode. Source: Ref 2.3 (top); Ref 2.4 (bottom)

In ac operation, one half of the voltage cycle operates as DCSP, and the other half operates as DCRP. In addition, it is possible to apply a small dc bias voltage on top of an ac voltage, thus shifting the half-cycles of the ac wave from being balanced between DCSP and DCRP to a slight DCSP bias. This accentuation of one or the other polarity to affect the welding as described for DCSP versus DCRP. This ac arc welding mode is known as *wave balance control*.

The effects of these different operating modes on the shape of the resulting molten weld pool are shown in profile in Fig. 2.3(b), as sections across a weld produced by a moving heat source:

- In DCSP mode (left), deep welds, with 70% of the heat of the arc found in the workpiece
- In DCRP mode (center), shallow welds and strong cleaning action at the workpiece surface from a scrubbing action by bombarding heavy ions, with 70% of the heat of the arc found in the welding electrode
- In ac mode (right), an intermediate profile with some surface cleaning

and fairly balanced distribution of heat from the arc in the welding electrode and in the workpiece

The welding machine, or power source, is the crux of the SMAW process. Its primary purpose is to provide electrical power of the proper current and voltage to maintain a controllable and stable welding arc. Its output characteristics must be of the constant current type. Shielded metal arc welding electrodes operate within the range from 25 to 500 A. The electrode producer should suggest a narrow optimum range for each size and type of electrode. Operating arc voltage varies between 15 and 35 V.

The electrodes used in the SMAW process have many different compositions of core wire and a wide variety of flux-covering types and weights. Standard electrode diameters of the core wire range from 1.6 to 8 mm (1/16 to 5/16 in.). Electrode length usually ranges from 230 to 455 mm (9 to 18 in.); the shorter lengths are associated with the smaller-diameter electrodes. A bare, uncoated end of the electrode (the grip end) is provided for making electrical contact in the electrode holder. The coating on the electrode provides:

- Gas (normally CO_2) from the decomposition of certain coating ingredients to shield the arc and weld zone from the atmosphere
- Deoxidizers for scavenging and purifying the deposited weld metal
- Slag formers to protect the deposited weld metal from atmospheric oxidation and to help shape the weld bead
- Ionizing elements to make the arc more stable and to operate with ac
- Alloying elements to provide special characteristics to the weld deposit
- Iron powder in certain electrodes, to increase productivity for welding ferrous metals

The American Welding Society (AWS) has established a system for identifying and classifying the different types of welding electrodes. All SMAW electrodes have the prefix letter E to indicate welding electrode. The symbols that follow the prefix are based on criteria that best describe the welding capabilities of the electrode metal. These criteria include chemical composition of the deposited weld metal, weld-metal mechanical properties, certain process parameters, or combinations of all factors.

2.2 Flux Cored Arc Welding

In the flux cored arc welding (FCAW) process, the heat for welding is produced by an electric arc between a continuous filler metal electrode and the workpiece. A tubular, flux-cored electrode makes this welding process unique. The flux contained within the electrode can make the electrode self-shielding. Alternatively, an external shielding gas may be required.

Flux cored arc welding has two major variations. The gas shielded FCAW process (Fig. 2.4) uses an externally supplied gas to assist in shielding the arc from nitrogen and oxygen in the atmosphere. Generally, the core ingredients in gas shielded electrodes are slag formers, deoxidizers, arc stabilizers, and alloying elements. In the self-shielded FCAW process, the core ingredients protect the weld metal from the atmosphere without external shielding. Some self-shielded electrodes provide their own shielding gas through the decomposition of core ingredients. Others rely on slag shielding, where the metal drops being transferred across the arc and the molten weld pool are protected from the atmosphere by a slag covering. Many self-shielded electrodes also contain substantial amounts of deoxidizing and denitrifying ingredients to help achieve sound weld metal. Self-shielded electrodes can also contain arc stabilizers and alloying elements.

Because it combines the productivity of continuous welding with the benefits of having a flux present, the FCAW process has several advantages relative to other welding processes:

- High deposition rates, especially for out-of-position welding
- Less operator skill required than for GMAW
- Simpler and more adaptable than submerged arc welding
- Deeper penetration than submerged arc welding
- More tolerant of rust and mill scale than GMAW

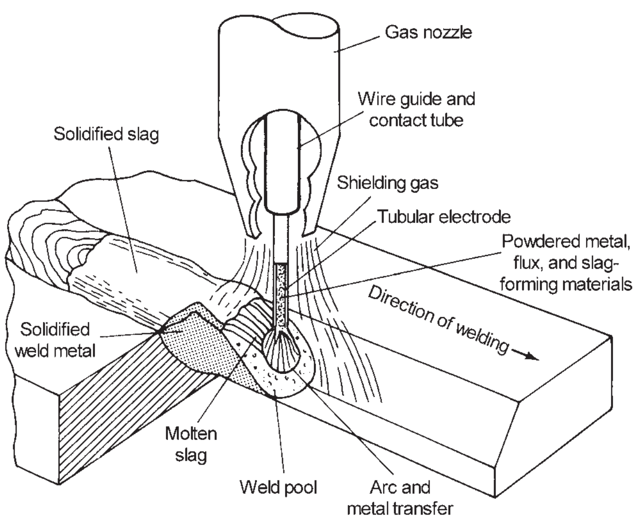

Fig. 2.4 Gas shielded flux cored arc welding. Source: Ref 2.3

Disadvantages of the FCAW process include:

- Slag must be removed from the weld and disposed
- More smoke and fume are produced in FCAW than in the GMAW and submerged arc welding processes
- Fume extraction is generally required
- Equipment is more complex and much less portable than submerged metal arc welding equipment

Most weldable carbon and low-alloy steels can be welded by the FCAW process if suitable electrodes are available. Steels for which electrodes are available include:

- Mild steels, such as AISI 1010 to 1030, ASTM A 36, A 285, A 515, and A 516
- Weathering structural steels, such as ASTM A 588
- High-strength, low-alloy steels, such as ASTM A 710
- High-temperature chromium-molybdenum steels, such as ASTM A 387 grades 12 (1Cr-0.5Mo) and 22 (2.25Cr-1Mo)
- Nickel-based steels, such as ASTM A 203
- High-strength quenched-and-tempered steels, such as HY-80 and ASTM A 514 and A 517
- Medium-carbon, heat-treatable, low-alloy steels, such as AISI 4130

The FCAW process uses semiautomatic, mechanized, and fully automatic welding systems. The basic equipment includes a power supply, wire feed system, and welding gun. The required auxiliary equipment, such as shielding gas, depends on the process variant used and the degree of automation. Fume removal equipment must also be considered in most applications of the FCAW process. Typical semiautomatic equipment is shown in Fig. 2.5. Mechanized and automatic FCAW equipment is not substantially different from that used in the semiautomatic FCAW process.

The recommended power supply for the semiautomatic FCAW process is a constant-voltage dc machine. Most power supplies used for semiautomatic FCAW have output ratings of $\leq$600 A. A power supply rated at $\geq$60% duty cycle is the best choice for most industrial applications, whereas a duty-cycle rating as low as 20% may be sufficient for maintenance and repair applications.

Wire feeders for constant-voltage FCAW systems are generally simple devices that provide a constant wire feed speed. The power supply provides sufficient current to maintain an arc at the voltage that is preset at the power supply. A change in wire feed speed results in a change in the welding current. In a constant-current system, the wire feeder is somewhat more complex. The welding current is preset at the power supply. The

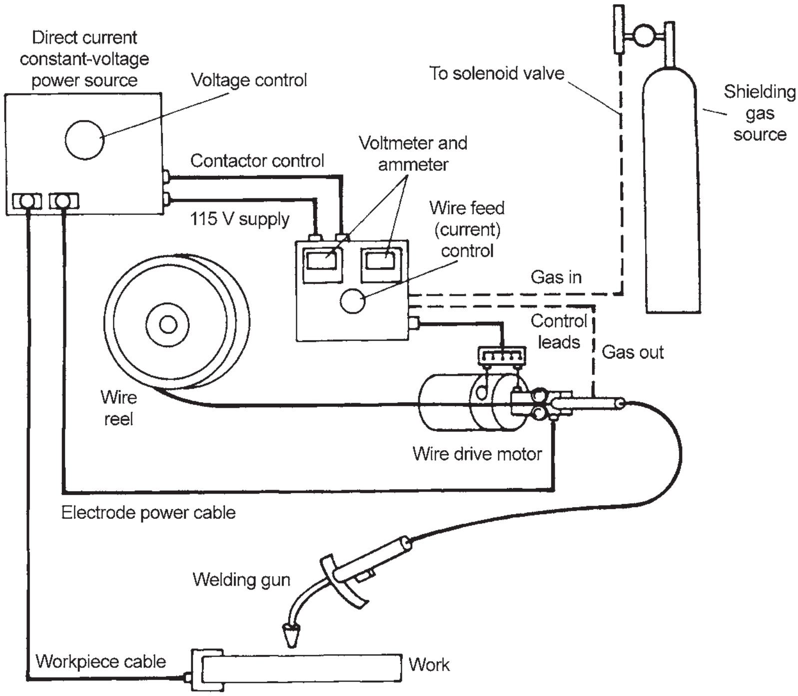

Fig. 2.5 Semiautomatic flux cored arc welding equipment. Source: Ref 2.3

wire feeder has a voltage-sensing feedback loop that allows it to adjust the wire feed speed to maintain the desired welding voltage. The wire feeder generally contains systems to close the contactor and open the shielding gas solenoid valve (gas shielded FCAW process only) when welding is started.

Both air-cooled and water-cooled welding guns are used in the semiautomatic FCAW process. Air-cooled guns are generally preferred because they are simpler to maintain, lighter in weight, and less bulky. Water-cooled guns may be required when welding currents >500 A are used, especially when the shielding gas is rich in argon. Air-cooled guns designed for gas shielded welding should not be used for self-shielded welding because the gun depends on the flow of shielding gas for proper cooling. Although curved-neck guns are the most common, straight guns are used to a limited extent.

Flux-cored electrode wire consists of a low-carbon steel sheath surrounding a core of fluxing and alloying material. Manufacture of flux-cored electrode wire is a specialized and precise operation. Most flux-cored electrode wire is made by passing low-carbon steel strip through contour-forming rolls that bend the strip into a U-shape cross section. The U-shape product is then filled with a measured amount of granular core material (flux) by passing it through a filling device. Next, the flux-filled

U-shape strip passes through closing rolls that form it into a tube and tightly compress the core materials. The tube is then pulled through drawing dies that reduce the diameter of the tube and further compress the core materials. The drawing operation secures the core materials inside the tube.

Functions of the compounds contained in the core are similar to those of the compounds in the coverings on the stick electrodes used for SMAW:

- Act as deoxidizers or scavengers to help purify the weld metal and produce a sound deposit
- Form slag to float on the molten weld metal and protect it from the atmosphere during solidification
- Act as arc stabilizers to produce a smooth welding arc and reduce weld spatter
- Add alloying elements to the weld metal to increase weld strength and provide other required weld-metal properties
- Provide shielding gas

Flux-cored electrodes are produced in diameters ranging from 0.8 to 3.2 mm (0.030 to 1/8 in.). Electrodes for all-position welding may be available in 0.8 mm (0.030 in.), 0.9 mm (0.035 in.), 1.2 mm (0.045 in.), 1.4 mm (0.052 in.), and 1.6 mm (1/16 in.) diameters. Electrodes for flat- and horizontal-position welding may be available in 1.6 mm (1/16 in.), 2.0 mm (5/64 in.), 2.4 mm (3/32 in.), 2.8 mm (7/64 in.), and 3.2 mm (1/8 in.) diameters.

Carbon dioxide (CO_2) is the most widely used shielding gas. Two advantages of this gas are its low cost and deep weld penetration. The gas mixture most commonly employed is 75% CO_2 and 25% Ar. Weld metal deposited with this mixture generally has higher tensile and yield strengths than weld metal deposited with 100% CO_2 shielding.

2.3 Submerged Arc Welding

Submerged arc welding is an arc welding process in which the arc is concealed by a blanket of granular and fusible flux. Heat for submerged arc welding is generated by an arc between a bare, solid-metal (or cored) consumable-wire or strip electrode and the workpiece. The arc is maintained in a cavity of molten flux or slag, which refines the weld metal and protects it from atmospheric contamination. Alloy ingredients in the flux may be present to enhance the mechanical properties and crack resistance of the weld deposit.

A typical setup for automatic submerged arc welding is shown in Fig. 2.6. A continuous electrode is fed into the joint by mechanically powered drive rolls. A layer of granular flux, just deep enough to prevent flash-through, is deposited in front of the arc. Electrical current, which produces

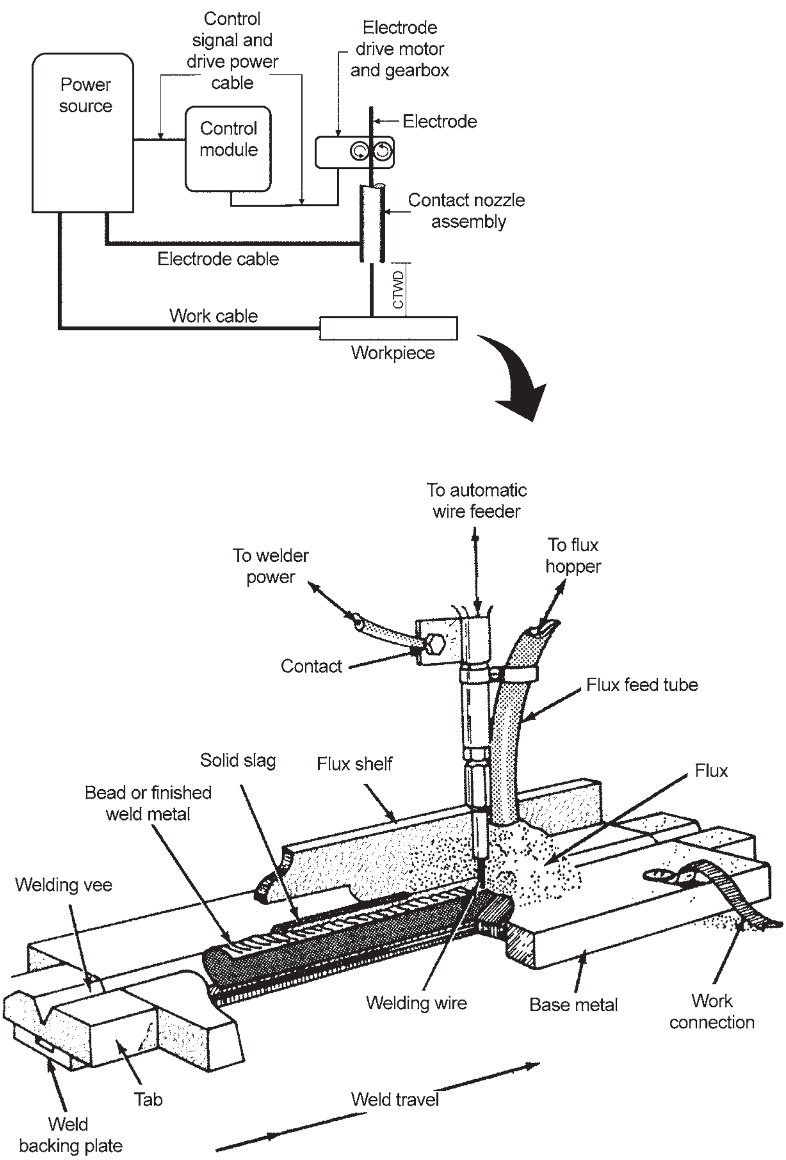

Fig. 2.6 Typical submerged arc welding equipment layout. CTWD, contact tip to work distance. Source: Ref 2.3 (bottom), Ref 2.5 (top)

the arc, is supplied to the electrode through the contact tube. The current can be dc with electrode positive (reverse polarity, or DCEP), dc with electrode negative (straight polarity, or DCEN), or alternating current (ac). After welding is completed and the weld metal has solidified, the unfused flux and slag are removed.

Submerged arc welding is adaptable to both semiautomatic and fully automatic operation, although the latter, because of its inherent advantages, is more popular. In semiautomatic welding, the welder controls the travel speed, direction, and placement of the weld. A semiautomatic welding gun is designed to transport the flux and wire to the operator, who welds by dragging the gun along the weld joint. Semiautomatic electrode diameters are usually <2.4 mm (<3/32 in.) to provide sufficient flexibility and feedability in the gun assembly. Manually guiding the gun over the joint requires skill because the joint is obscured from view by the flux layer. In automatic submerged arc welding, travel speed and direction are controlled mechanically. Flux may be automatically deposited in front of the arc, while the unfused flux may be picked by a vacuum recovery system behind the arc.

Advantages of submerged arc welding include:

- The arc is under a blanket of flux, which virtually eliminates arc flash, spatter, and fume, making the process attractive from an environmental standpoint.
- High current densities increase penetration and decrease the need for edge preparation.
- High deposition rates and travel speeds are possible.
- Cost per unit length of joint is relatively low.
- The flux acts as a scavenger and deoxidizer to remove contaminants such as oxygen, nitrogen, and sulfur from the molten weld pool. This helps to produce sound welds with excellent mechanical properties.
- Low-hydrogen weld deposits can be produced.
- The shielding provided by the flux is substantial and is not sensitive to wind as in SMAW and GMAW.
- Minimal welder training is required, and relatively unskilled welders can be employed.
- The slag can be collected, reground, and sized for mixing back into new flux as prescribed by manufacturers and qualified procedures.

Limitations of submerged arc welding include:

- The initial cost of wire feeder, power supply, controls, and flux-handling equipment is high.
- The weld joint needs to be placed in the flat or horizontal position to keep the flux positioned in the joint.
- The slag must be removed before subsequent passes can be deposited. Because of the high heat input, submerged arc welding is most commonly used to join steels more than 6.4 mm (1/4 in.) thick.

If a steel is suitable for GMAW, FCAW, SMAW, or GTAW, procedures can be developed to weld the steel with submerged arc welding. The main limitations are plate thickness and position. Because submerged arc welding is a high heat input and high deposition rate process, it is generally used to weld thicker-section steels. Although the welding of steel as thin as 1.6 mm (1/16 in.) is possible, most submerged arc welding is done on plate over 6.4 mm (1/4 in.) in thickness.

Fluxes can be categorized depending on the method of manufacture and the extent to which they can affect the alloy content of the weld deposit. Based on the manufacturing process, there are two different types of fluxes: fused and bonded. The raw materials for a fused flux are dry mixed and melted in a furnace. The molten mixture is then rapidly solidified, crushed, screened, and packaged. Because of their method of manufacture, fused fluxes typically do not contain ferroalloys and deoxidizers. The powdered ingredients of a bonded flux are dry blended and then mixed with a binder, usually potassium or sodium silicate. After pelletizing, the wet flux is dried in an oven or kiln, sized appropriately, and then packaged. The relatively low baking temperatures allow bonded fluxes to contain deoxidizers and ferroalloys.

Independent of manufacturing method, a given flux may be described as an active, neutral, or alloy flux, depending on its ability to change the alloy content of the weld deposit. With all submerged arc fluxes, variations in arc voltage and other welding variables will change the ratio of flux consumed to electrode or weld metal deposited. This ratio is often referred to as the *flux-to-wire ratio.* Normal flux-to-wire ratios are 0.7 to 0.9. An increase in the flux-to-wire ratio may be caused by either an increase in arc voltage or a decrease in the welding current. Likewise, a decrease in the flux-to-wire ratio may be caused by a decrease in arc voltage or an increase in the welding current. How the weld deposit composition changes with voltage (flux-to-wire ratio) provides an additional means of describing a flux.

Active fluxes contain controlled amounts of manganese and/or silicon. These alloys are added as ingredients in the flux to provide improved resistance to porosity and weld cracking caused by contaminants such as oxygen, nitrogen, and sulfur on the plate or in the plate composition itself. Active fluxes are primarily used to make single-pass welds. Because active fluxes contain deoxidizers such as manganese and silicon, the alloy in the weld metal will change with the flux-to-wire ratio. Changes in manganese and silicon content in the weld deposit will affect the strength and impact properties of the weld metal; therefore, the arc voltage must be more tightly controlled when welding with active fluxes than with neutral fluxes.

Neutral fluxes contain little or no deoxidizers and, by definition, will not produce any significant change in the weld metal composition as a result of a large change in arc voltage. Because neutral fluxes contain little or no alloy, they must rely on alloy in the electrode to provide deoxidation. Single-pass welds on oxidized plate may be prone to cracking or porosity because of insufficient alloy content and are usually best welded with active fluxes. Neutral fluxes are primarily used for multipass welding on plate exceeding 25 mm (1 in.) in thickness.

Alloy fluxes contain enough alloy as a flux ingredient to produce an alloy weld metal with a carbon steel electrode. They are also used with alloy and stainless steel wire and strip electrodes. Alloy fluxes are primarily used in welding alloy steels and hardfacing. Because the alloy in the weld deposit is a function of arc voltage (flux-to-wire ratio), it is important to follow the manufacturer's recommended procedure for obtaining proper weld deposit composition.

There are three different types of consumable electrodes: solid wire, cored wire, and strip. Electrodes are available for welding carbon steel, low-alloy steel, stainless steel, and nickel-based alloys. Wire diameters vary from 1.6 to 6.4 mm (1/16 to 1/4 in.). Carbon steel wire usually has a light copper coating, which protects the wire from corrosion and provides good electrical contact in the welding tip. Cored electrodes were developed to provide a low-cost method of increasing the number of alloys that can be welded. Cored electrodes typically consist of a mild steel tube with alloying elements in the center. Compositions of cored electrodes vary from mild and low-alloy steels through tool steels to stainless steels and high-alloy austenitic steels. Strip electrodes are generally used for welding overlays and for hardfacing applications. The advantages of strip are wide weld beads, low penetration, low dilution, and high deposition rates. The equipment is very similar to submerged arc welding with wire except that special drive rolls are needed to feed the strip, and sometimes auxiliary magnetic fields are set up to improve bead shape and tie-in. Strip thicknesses vary from 0.5 to 1.0 mm (0.02 to 0.04 in.), and widths vary from about 25 to 100 mm (1 to 4 in.).

Fluxes usually are designed to operate with either ac or dc. The type of welding current used has an effect on all weld properties. Joint penetration (and resulting dilution) are greatly affected by the type of welding current (DCEP or DCEN) used. The joint penetration will change with type of current used; however, that change will be influenced by the current range and flux type. Most submerged arc fluxes are designed for alternating current or DCEN. The amount of flux fused per minute in submerged arc welding depends on the welding current and voltage. For a given current, the amount of flux fused per minute increases with voltage. Depth of flux layer affects the shape and penetration of welds, as shown in Fig. 2.7. When the flux layer is too shallow (Fig. 2.7a), the arc is exposed and a cracked or porous weld results. When the flux is too deep (Fig. 2.7c), the result is peaked weld beads with above-average joint penetration. When the flux is neither too shallow nor too deep, very faint flashes appear around the interface between the electrode wire and the flux, and the weld bead appears as shown in Fig. 2.7b.

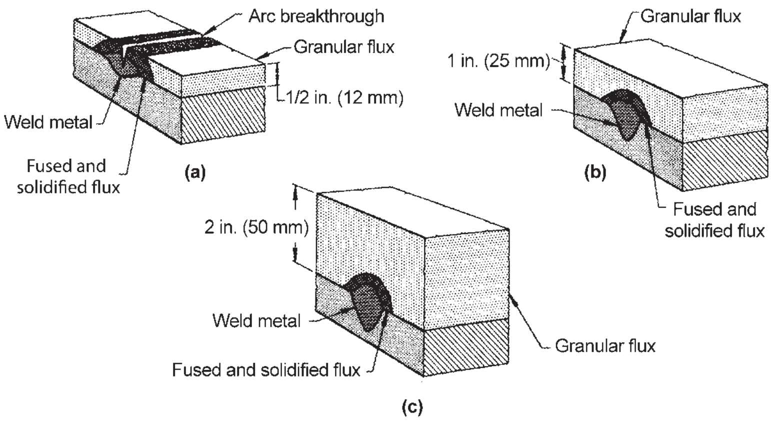

Fig. 2.7 Effect of depth of flux layer on shape and penetration of submerged arc surface welds made at 800 A. (a) Flux layer too shallow, resulting in arc breakthrough (from loss of shielding), shallow penetration, and weld porosity or cracking. (b) Flux layer at correct depth for good weld-bead shape and penetration. (c) Flux layer too deep, resulting in peaked weld bead with above-average penetration. Source: Ref 2.3

2.4 Gas Metal Arc Welding

Gas metal arc welding (GMAW), which is also commonly referred to as MIG (metal inert gas) welding, is an arc welding process that joins metals together by heating them with an electric arc that is established between a consumable electrode (wire) and the workpiece. An externally supplied gas or gas mixture acts to shield the arc and molten weld pool. The GMAW process can be operated in semiautomatic and automatic modes. All commercially important metals, such as carbon steel, high-strength low-alloy (HSLA) steel, stainless steel, aluminum, copper, and nickel alloys, can be welded in all positions by this process if appropriate shielding gases, electrodes, and welding parameters are chosen.

The applications of the process are dictated by its advantages, the most important of which are:

- Electrode length does not face the restrictions encountered with SMAW.
- Welding can be accomplished in all positions, when the proper parameters are used, a feature not found in submerged arc welding.
- Travel speeds are higher than those of the SMAW process.
- Deposition rates are significantly higher than those obtained by the SMAW process.
- Continuous wire feed enables long welds to be deposited without stops and starts.
- Penetration deeper than with the SMAW process is possible, which may permit the use of smaller-sized fillet welds for equivalent strengths.

- Less operator skill is required than for other conventional processes, because the arc length is maintained constant with reasonable variations in the distance between the contact tip and the workpiece.
- Minimal postweld cleaning is required because of the absence of a heavy slag.

These advantages make the process particularly well suited to high-production and automated welding applications. With the advent of robotics, GMAW has become the predominant process choice.

The GMAW process, like any welding process, has certain limitations that restrict its use:

- The welding equipment is more complex, usually more costly, and less portable than SMAW equipment.
- The process is more difficult to apply in hard-to-reach places because the welding gun is larger than an SMAW holder and must be held close to the joint (within 10 to 19 mm, or 3/8 to 3/4 in.) to ensure that the weld metal is properly shielded.
- The welding arc must be protected against air drafts that can disperse the shielding gas, which limits outdoor applications unless protective shields are placed around the welding area.
- Relatively high levels of radiated heat and arc intensity can hinder operator acceptance of the process.

In the GMAW process (Fig. 2.8), an arc is established between a continuously fed electrode of filler metal and the workpiece. After proper settings are made by the operator, the arc length is maintained at the set value, despite the reasonable changes that would be expected in the gun-to-work distance during normal operation. This automatic arc regulation is achieved in one of two ways. The most common method is to use a constant-speed (but adjustable) electrode feed unit with a variable-current (constant-voltage) power source. As the gun-to-work relationship changes, which instantaneously alters the arc length, the power source delivers either more current (if the arc length is decreased) or less current (if the arc length is increased). This change in current will cause a corresponding change in the electrode melting rate, thus maintaining the desired arc length. The second method of arc regulation uses a constant-current power source and a variable-speed, voltage-sensing electrode feeder. In this case, as the arc length changes, there is a corresponding change in the voltage across the arc. As this voltage change is detected, the speed of the electrode feed unit will change to provide either more or less electrode per unit of time. This method of regulation is usually limited to larger electrodes with lower feed speeds.

The type of arc obtainable in GMAW is identified by the mode of metal transfer. These modes of transfer are commonly referred to as spray, globular, short-circuiting, and pulsed-current transfer.

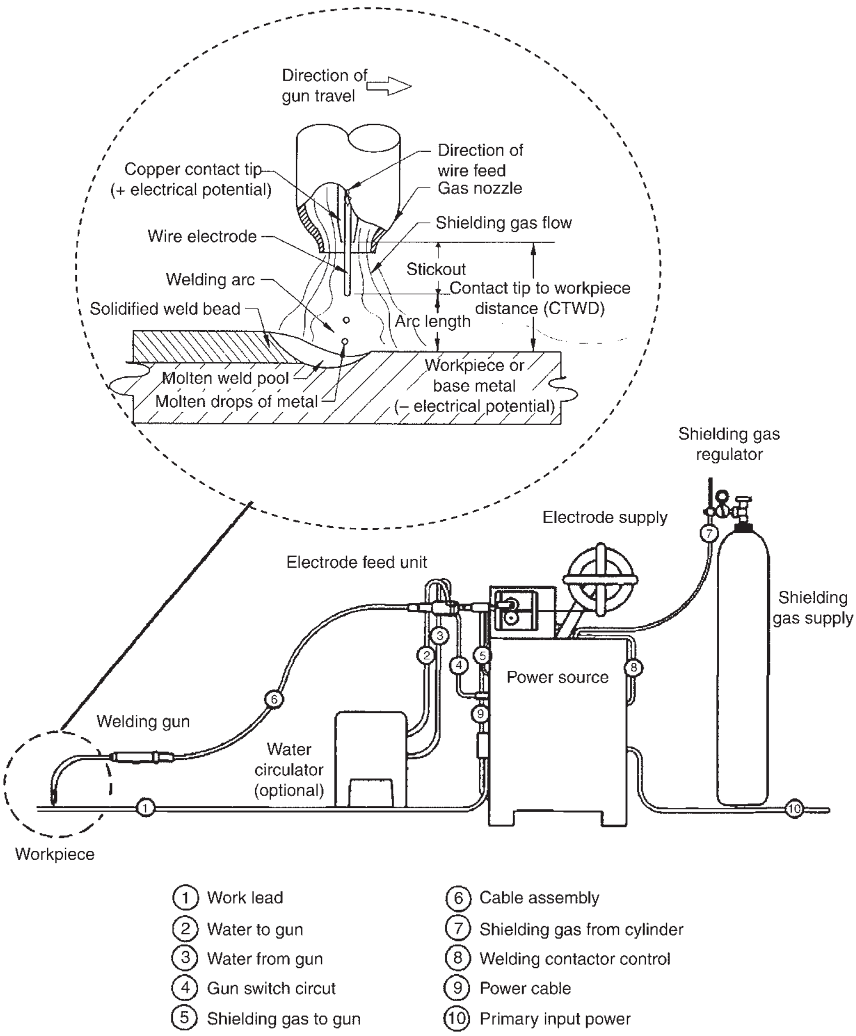

Fig. 2.8 Schematic of gas metal arc welding process. Source: Ref 2.6

In the *spray transfer* mode, metal is transferred from the end of the electrode wire to the pool in an axial stream of fine droplets (Fig. 2.9a). These small droplets emanate from the tapered end of the electrode; one droplet follows another, but they are not connected. The size of the droplets may vary, but in a spray arc the maximum diameter is less than that of the electrode wire. The spray arc occurs at high current density, generally with argon or an argon-rich shielding gas. A true spray arc cannot be obtained with a shielding gas composed of more than 10 to 15% CO_2. The spray transfer mode gives high heat input, maximum penetration, and a high deposition rate. In welding of steel, it generally is limited to welding in the flat position and the horizontal fillet position. This mode also produces the least amount of spatter.

Globular transfer occurs at lower current densities and is characterized by the formation of a relatively large drop of molten metal at the end of the tapered electrode wire (Fig. 2.9b). The drop forms at the end of the electrode wire until the force of gravity overcomes the surface tension of the molten drop, at which time the drop falls into the weld pool.

Short-circuiting transfer is used in many applications of GMAW. It is especially well adapted to welding thin sections because heat input is low; it is less often used for welding thick sections. This mode of transfer permits welding in any position and occurs with CO_2, Ar-CO_2 mixtures, and helium-base shielding gases. Steps that occur with the short-circuiting mode of transfer are shown in Fig. 2.9(c) to (f). At the start of the short-circuiting arc cycle, the end of the electrode wire melts into a small globule of liquid metal (Fig. 2.9c). The drop advances toward the weld pool, makes contact with the weld pool causing a short circuit, The drop then detaches into the weld pool while a new drop starts forming on the welding electrode (Fig. 2.9d–f).

Pulsed-current transfer is a spray-type transfer that occurs in pulses at regularly spaced intervals rather than at random intervals. In the time in-

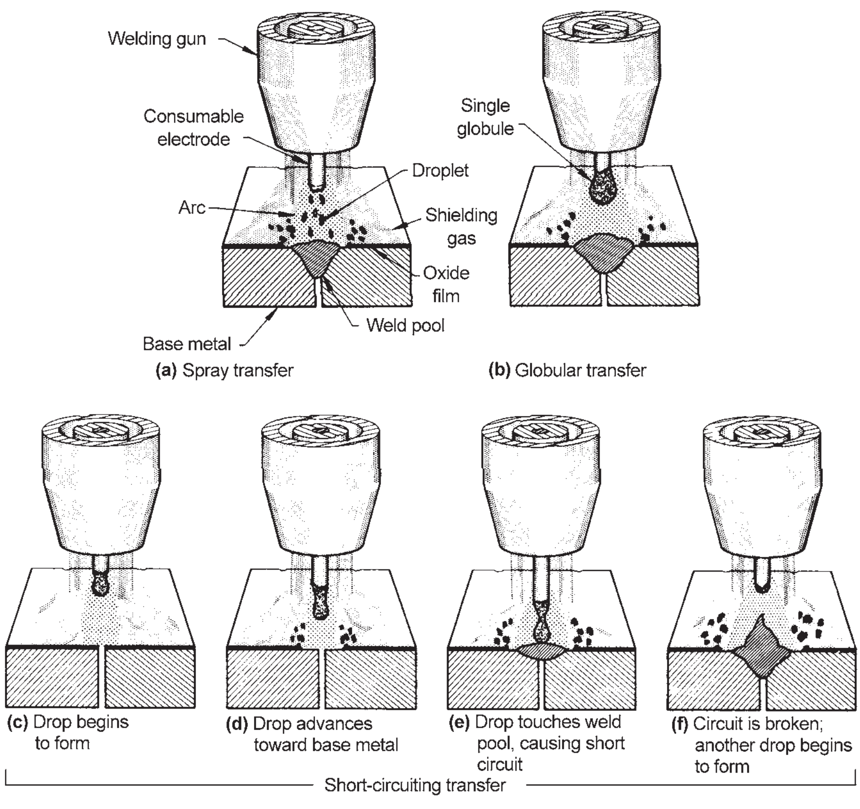

Fig. 2.9 Modes of metal transfer in gas metal arc welding: (a) spray transfer; (b) globular transfer; and (c), (d), (e), and (f) steps in short-circuiting transfer. Source: Ref 2.3

terval between pulses, the welding current is reduced and no metal transfer occurs. The pulsing action is obtained by combining the outputs of two power supplies working at two current levels. One acts as a background current to preheat and precondition the advancing continuously fed electrode; the other power supply furnishes a peak current for forcing the drop from the electrode to the joint being welded. The peaking current is half-wave dc; because it is tied into line frequency, drops will be transferred from the electrode to the joint 60 to 120 times per second.

Most GMAW applications require dc with electrode positive (DCEP) operating mode. This type of electrical connection provides a stable arc, smooth metal transfer, relatively low spatter loss, and good weld-bead characteristics for the entire range of welding currents used. Direct current electrode negative (DCEN) is seldom used, because the arc can become very unstable and erratic even though the electrode melting rate is higher than that achieved with DCEP. Penetration is lower with DCEN than with DCEP. Alternating current is not normally used for two reasons: (1) the arc is extinguished during each half cycle as the current reduces to zero, and it may not reignite if the cathode cools sufficiently; and (2) rectification of the reverse-polarity cycle promotes erratic arc operation.

The welding power source provides suitable electrical power (generally 20 to 80 V) that is delivered to the electrode and workpiece to produce the arc. Because the vast majority of applications use DCEP, the positive lead is connected to the gun and the negative lead to the workpiece. The power source can be the “static” type in which incoming utility power (120 to 480 V) is reduced to welding voltage by a transformer or solid-state inverter. It could also be the “rotating” type in which the welding power is provided by a rotating generator driven by a motor or internal combustion engine. The static type is normally used in shops where there is an available source of power. It has the advantage over the rotating type in that it can respond more rapidly to varying arc conditions. The rotating type is generally used at field sites where external power is unavailable. Both types of power sources can be designed and built to provide either a constant current or constant potential (cp) output, the latter of which is the most common by far.

The welding gun used in GMAW transmits welding current to the electrode. Because the wire is fed continuously, a sliding electrical contact is used. The welding current is passed to the electrode through a copper alloy contact tube. The contact tubes have various hole sizes, corresponding to the diameter of the electrode wire. The gun also has a gas-supply connection and a nozzle to direct the shielding gas around the arc and weld pool. To prevent overheating of the welding gun, cooling is required to remove the heat generated. Shielding gas, water circulating in the gun, or both are used for cooling. Some guns are also air cooled. Handheld semiautomatic guns usually have a curved neck (Fig. 2.10), which makes them applicable to all welding positions. The gun is attached to the service

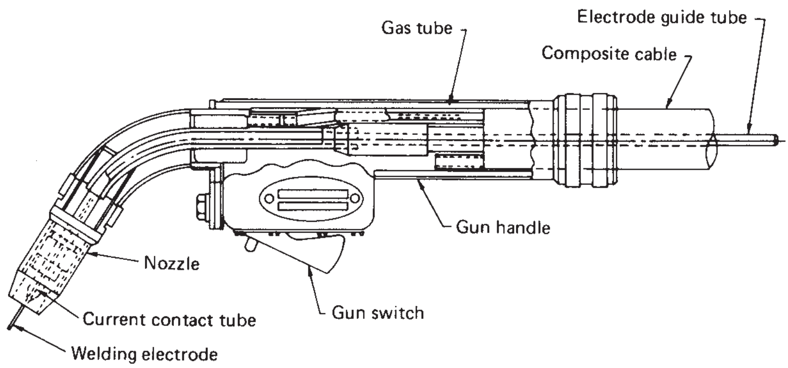

Fig. 2.10 Typical semiautomatic gas-cooled, curved-neck gas metal arc welding gun. Source: Ref 2.6

lines, which include the power cable, water hose, gas hose, and wire conduit or liner. The guns have metal nozzles that have orifice diameters from 9.5 to 22 mm (3/8 to 7/8 in.) to direct the shielding gas to the arc and weld pool, depending on the welding requirements.

The electrodes for GMAW are usually quite similar or identical in composition to those used for welding by most other bare electrode processes. In many cases, the electrode wires are chosen to match the chemical composition of the base metal as closely as possible. In some cases, electrodes with a somewhat different chemical composition are used to obtain maximum mechanical properties or better weldability. Composition of electrode wire has a significant effect on results. Because of the importance of electrode composition, many large users of electrode wire have established their own specifications, which they have developed from their own experience.

The primary function of the shielding gas in most of the welding processes is to protect the surrounding atmosphere from contact with molten metal. In the GMAW process, this gas plays an additional role in that it has a pronounced effect on arc characteristics, mode of metal transfer, depth of fusion, weld bead profile, travel speed, and cleaning action. Inert gases, such as argon and helium, are commonly used, as is the active gas CO_2. It is also common to use mixtures of these gases and to employ small additions of oxygen.

2.5 Gas Tungsten Arc Welding

Gas tungsten arc welding (GTAW), often called TIG (tungsten inert gas) welding, tungsten arc welding, or HeliArc welding, is an arc welding process in which the heat is produced between a nonconsumable tungsten alloy electrode and the work metal (Fig. 2.11). The electrode, weld pool, arc, and adjacent heated areas of the workpiece are protected from atmo-

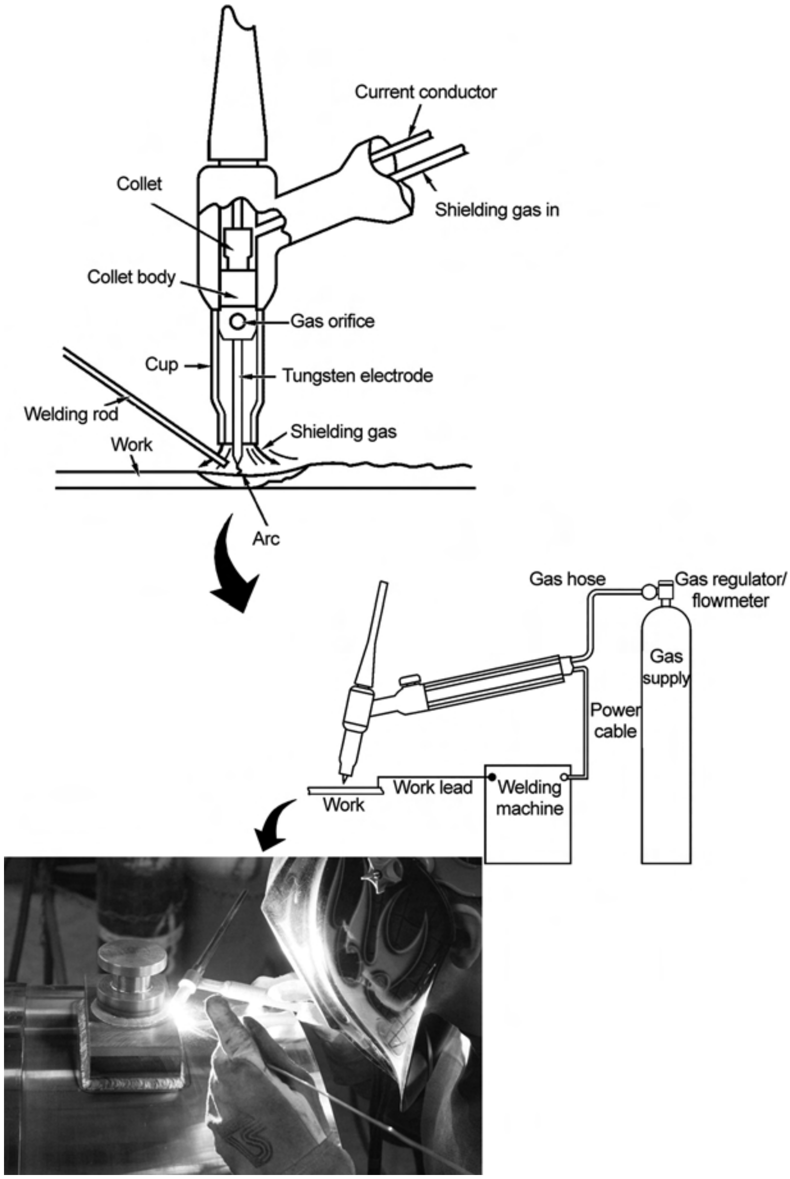

Fig. 2.11 Key components of the gas tungsten arc welding process. Source: Ref 2.7

spheric contamination by a gaseous shield. This shield is provided by a stream of gas, usually an inert gas or a mixture of gases. The gas shield must provide full protection; even a small amount of entrained air can contaminate the weld.

Gas tungsten arc welding is used extensively for welding stainless steel, aluminum, magnesium, copper, and reactive materials such as titanium and tantalum. The process can also be used to join carbon and alloy steels.

In carbon steels, it is primarily used for root pass welding with the application of consumable inserts or open-root techniques on pipe. The materials welded range from a few thousandths of an inch to several inches in thickness.

Advantages of GTAW include:

- Produces high-quality, low-distortion welds
- Free of the spatter associated with other methods
- Can be used with or without filler wire
- Can be used with a range of power supplies
- Welds almost all metals, including dissimilar ones
- Gives precise control of welding heat

The GTAW process is applicable when the highest weld quality is required. It can be used to weld almost all types of metals. The operator has excellent control of heat input, and vision is not limited by fumes or smoke from the process.

Limitations of GTAW include:

- Produces lower deposition rates than consumable electrode arc welding processes
- Requires slightly more dexterity and welder coordination than GMAW or SMAW for manual welding
- Less economical than consumable electrode arc welding for thick sections >9.5 mm (>3/8 in.)
- Problematic in drafty environments because of difficulty in shielding the weld zone properly

Additional problems with the process may include:

- Tungsten inclusions if the electrode is allowed to contact the weld pool
- Contamination of the weld metal, if proper shielding of the filler metal by the gas stream is not maintained
- Low tolerance for contaminants on filler or base metals
- Contamination or porosity caused by coolant leakage from water-cooled torches
- Arc blow or arc deflection can be a problem

Current is one of the most important operating conditions to control in any welding operation because it is related to the depth of penetration, travel speed, deposition rate, and quality of the weld. The three choices of welding current for GTAW are DCEN, DCEP, and ac. The setups for DCEN and DCEP are shown in Fig. 2.12 and resulting weld bead formations are shown in Fig. 2.13. The recommended current types for different metals are summarized in Table 2.1.

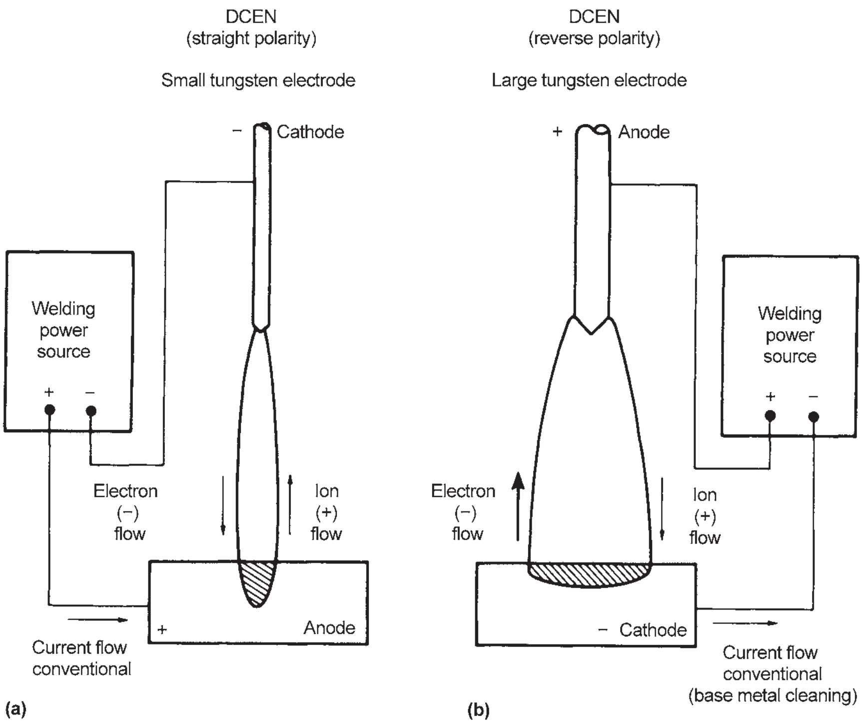

Fig. 2.12 Effect of polarity on gas tungsten arc welding weld configuration when using direct current: (a) direct current electrode negative (DCEN), deep penetration, narrow melted area, approximate 30% heat in electrode and 70% heat in base metal; (b) direct current electrode positive (DCEP), shallow penetration, wide melted area, approximate 70% heat in electrode and 30% heat in base metal. Source: Ref 2.8

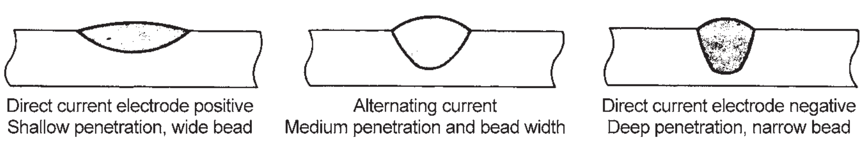

Fig. 2.13 Weld configuration as a function of type of current used. Source: Ref 2.8

Alternating current is characterized as reversing the polarity of the work and electrode at 60 Hz. The rapidly changing polarity gives a cathodic cleaning action that is beneficial for oxide removal when welding aluminum and magnesium. The ac results in electrode heating during the DCEP portion of each cycle. This necessitates the use of larger-diameter electrodes, normally made of pure tungsten. Variable polarity welding allows the frequency of polarity switching to be preset. This can produce the cleaning effects of ac welding and the high efficiency of dc welding. Direct current electrode negative is most often used in the GTAW process.

Table 2.1 Suitability of types of current for gas tungsten arc welding of selected metals

Metal welded	Alternating current(a)	DCEN	DCEP
Low-carbon steel			
0.38–0.76 mm (0.015–0.030 in.)(a)	G(b)	E	NR
0.76–3.18 mm (0.030–0.125 in.)	NR	E	NR
High-carbon steel	G(b)	E	NR
Cast iron	G(b)	E	NR
Stainless steel	G(b)	E	NR
Heat-resistant alloys	G(b)	E	NR
Refractory metals	NR	E	NR
Aluminum alloys			
≤0.64 mm (0.025 in.)	E	NR(c)	G
>0.64 mm (0.025 in.)	E	NR(c)	NR
Castings	E	NR(c)	NR
Beryllium	G(b)	E	NR
Copper and alloys			
Brass	G(b)	E	NR
Deoxidized copper	NR	E	NR
Silicon bronze	NR	E	NR
Magnesium alloys			
≤3.2 mm (1/8 in.)	E	NR(c)	G
>4.8 mm (3/16 in.)	E	NR(c)	NR
Castings	E	NR(c)	NR
Silver	G(b)	E	NR
Titanium alloys	NR	E	NR

Abbreviations: DCEN, dc electrode negative; DCEP, dc electrode positive; E, excellent; G, good; NR, not recommended. (a) Stabilized. Do not use alternating current on tightly jigged assemblies. (b) Amperage should be about 25% higher than when DCEN is used. (c) unless work is mechanically or chemically cleaned in the areas to be welded. Source: Ref 2.3

This results in maximum application of heat to the work and maximum melting of the workpiece.

Nonpulsed or continuous current is the standard for GTAW. However, there are several advantages to using pulsed current. Pulsing produces the maximum amount of penetration while minimizing the total heat applied to the part. Pulsing also aids in timing the motion necessary in manual welding and allows the weld pool to cool between pulses.

Power supplies for GTAW are usually the constant-current type with a drooping (negative) volt/ampere (V/A) curve. Saturable reactors and thyristor-controlled units are the most common. Transistorized dc (dc) power supplies are common, and the newer rectifier-inverter supplies are very compact and versatile. The inverter power supply consists of three converters: 60 Hz primary ac is rectified to dc, dc is inverted to high-frequency ac, and ac is rectified to dc. The inverter supplies can be switched from constant current to constant voltage, resulting in a very versatile piece of equipment. The inverter-controlled power supplies are more stable and have faster response times than conventional silicon-controlled rectifier (SCR) power supplies.

The welding torch holds the tungsten electrode that conducts the current to the arc, and it provides a means of shielding the arc and molten metal. Welding torches rated at less than 200 A are normally gas cooled (i.e., the shielding gas flows around the conductor cable, providing the necessary cooling). Water-cooled torches are used for continuous operation or at higher welding currents and are common for mechanized or automatic welding. The cooling water may be supplied to the torch from a recirculating tank that uses a radiator or chiller to cool the water.

The nonconsumable electrodes used in GTAW are composed of tungsten or alloys of tungsten. The most common electrode is a 2% ThO_2-W alloy (EWTh-2). This material has excellent operating characteristics and good stability. Thorium dioxide (ThO_2) is radioactive, so care must be taken when sharpening electrodes not to inhale metal dust. The grindings are considered hazardous waste in some states, and disposal may be subject to environmental regulations. Lanthanated (EWLa-1) and yttriated tungsten electrodes have the best starting characteristics in that an arc can be started and maintained at a lower voltage. Ceriated tungsten (EWCe-2) is only slightly better than thoriated tungsten with respect to arc starting and melting rate. Any of these electrodes produce acceptable welds.

Pure tungsten is used primarily in ac welding and has the highest consumption rate. Alloys of zirconium are also used. Tungsten electrodes are classified on the basis of their chemical composition (Table 2.2). Requirements for tungsten electrodes are given in the latest edition of AWS specification A5.12/5.12M (Ref 2.9). The shape of the electrode tip can affect the resulting weld shape. Electrodes with included angles from 60 to 120° are stable and give good weld penetration depth-to-width ratios. Electrodes with smaller included angles (5 to 30°) are used for grooved weld joints to eliminate arcing to the part side walls.

Argon, the most commonly used gas for GTAW, exhibits low thermal conductivity, which produces a narrow, constricted arc column; this allows greater variations in arc length with minimal influence on arc power or weld bead shape. Its low ionization potential provides good arc starting characteristics and good arc stability using the DCEN power connection plus superior arc cleaning action and bead appearance when ac power is used. Argon is the most commonly selected gas for DCEN welding of most materials and ac manual welding of aluminum. The high thermal conductivity and ionization potential of helium make it suitable for the high-current joining of heavy sections of heat-conductive materials such

Table 2.2 Classification of alloying elements in selected tungsten alloy electrodes for gas tungsten arc welding

AWS classification	Color(a)	Alloying element	Alloying oxide	Alloying oxide, wt%
EWP	Green	...	...	
EWCe-2	Orange	Cerium	CeO_2	2
EWLa-1	Black	Lanthanum	La_2O_3	1
EWTh-1	Yellow	Thorium	ThO_2	1
EWTh-2	Red	Thorium	ThO_2	2
EWZr-1	Brown	Zirconium	ZrO_2	0.25
EWG	Gray	Not specified(b)	...	...

(a) Color may be applied in the form of bands, dots, and so on, at any point on the surface of the electrode. (b) Manufacturer must identify the type and nominal content of the rare-earth oxide addition. Source: Ref 2.3

as aluminum. Helium increases the penetration of the weld as well as its width. It also allows the use of higher weld travel speeds. Blends of argon and helium are selected to increase the heat input to the base material while maintaining favorable arc stability and superior arc starting characteristics. Blends of 25, 50, and 75% He in argon are commonly used. Hydrogen is added to argon to enhance its thermal properties. The slightly reducing atmosphere improves weld puddle wetting and reduces some surface oxides to produce a cleaner weld surface. To minimize problems associated with arc starting, additions of hydrogen are generally limited to 5 to 15%. These blends are primarily used to join some stainless steels, nickel, and nickel alloys. These mixtures should not be used to join alloy steels as delayed weld cracking may result. Argon with additions of 2 to 5% H_2 is used in manual welding applications on materials thicker than 1.6 mm (1/16 in.). Additions of 10 to 15% H_2 are used in mechanized applications, such as those found in the manufacture of stainless steel tubing.

The thickness of the part to be welded will determine the need for filler metal additions. Material thinner than 3.2 mm (0.125 in.) can be successfully welded without filler metal additions. Filler metal, when needed, can be added manually in straight length or automatically from a roll or coil. The filler metal is normally added cold; however, hot wire can be used for automatic applications.

2.6 Plasma Arc Welding

Plasma arc welding (PAW) can be defined as a gas shielded arc welding process where the coalescence of metals is achieved via the heat transferred by an arc that is created between a tungsten electrode and a workpiece. The arc is constricted by a copper alloy nozzle orifice to form a highly collimated arc column (Fig. 2.14). The plasma is formed through the ionization of a portion of the plasma (orifice) gas. The process can be operated with or without a filler wire addition.

The PAW process is commonly used to weld stainless steels in a wide range of thicknesses. The process can also be used with carbon and alloy steels, aluminum alloys, titanium alloys, copper and nickel alloys, and more specialized materials, such as zirconium and tantalum. The thicknesses that can be welded in a single pass range from 0.025 to 12.5 mm (0.001 to 0.5 in.), depending on the mode of operation and the metal being welded.

Once the equipment is set up and the welding sequence is initiated, the plasma and shielding gases are switched on. A pilot arc is then struck between a tungsten alloy electrode and the copper alloy nozzle within the torch (nontransferred arc mode), usually by applying a high-frequency open-circuit voltage. When the torch is brought in close proximity to the

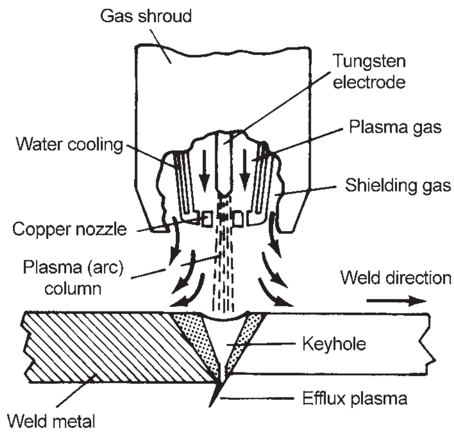

Fig. 2.14 Plasma arc welding process, showing constriction of the arc by a copper nozzle and a keyhole through the plate. Source: Ref 2.10

workpiece or when the selected welding current is initiated, the arc is transferred from the electrode to the workpiece through the orifice in the copper alloy nozzle (transferred arc mode), at which point a weld pool is formed.

The PAW process can be used in two distinct operating modes, often described as the melt-in mode and the keyhole mode. The melt-in mode refers to a weld pool similar to that which typically forms in the GTAW process, where a bowl-shaped portion of the workpiece material that is under the arc is melted. In the keyhole mode, the arc fully penetrates the workpiece material, forming a nominally concentric hole, or keyhole, through the thickness. The molten weld metal flows around the arc and resolidifies behind the keyhole as the torch traverses the workpiece.

The PAW process uses three current modes: microplasma (melt-in mode), medium-current plasma (melt-in mode), and keyhole plasma (keyhole mode). This categorization is primarily based on the level of welding current. The microplasma mode is usually defined in the current range from 0.1 to 15 A. The medium-current plasma mode ranges from 15 to 100 A. The keyhole plasma mode is above 100 A. There is a certain degree of overlap between these current ranges. For example, keyholing can be achieved at 70 A on a 2 mm (0.08 in.) sheet. Equipment is available for welding currents up to 500 A, although a 300 A maximum is typical. Microplasma and medium-current melt-in modes are used for material up to 3 mm (0.12, or 1/8, in.) thick, whereas the keyhole plasma mode is used for greater thicknesses and higher travel speeds.

In addition to operating in a continuous and steady dc electrode negative (DCEN) mode, the PAW process can be carried out using DCEN pulsed current, as well as in the variable polarity mode, which uses both DCEP and electrode negative polarity switching. The pulsed current mode (both DCEN and DCEN/DCEP) is most often used when current levels (typically, above 100 A) are employed for keyhole plasma welding.

The electrode positive component of the variable polarity plasma arc (VPPA) welding process promotes cathode etching of the tenacious surface oxide film when welding aluminum alloys, allowing good flow characteristics and consistent bead shape. Pulsing times are typically 20 ms for the electrode negative component and 3 ms for the electrode positive polarity. The VPPA welding process is used very effectively in specialized aerospace applications.

The PAW process is generally used when the high penetration of the keyhole welding mode can be exploited to minimize the number of welding passes and hence welding time. The time saved can reduce the direct labor element of the welding operation. At the other end of the scale, the microplasma operating mode is used to weld small, thin-section components (as low as 0.025 mm, or 1 mil, thick), where the high arc constriction and low welding current can be beneficial in controlling heat input and distortion.

Advantages of the PAW process are primarily intrinsic to the keyhole mode of operation, because greater thicknesses of metal can be penetrated in a single pass, compared with other processes, such as GTAW. This greater amount of penetration allows a reduced amount of joint preparation. For example, in some materials a square-grooved butt joint preparation can be used for thicknesses up to 12 mm (0.5 in.). The process can produce high weld integrity (similar to GTAW) while minimizing weld passes and hence welding times and labor costs. The columnar shape of the arc results in a greater tolerance to variations in torch standoff distance compared with the conical arc shape of a GTAW arc. The tungsten electrode used in the PAW process is protected from contamination by the constricting nozzle (Fig. 2.14). The longer arc length allows better viewing of the weld pool, which is important in manual welding.

Disadvantages include the greater capital equipment cost compared with its main rival, the GTAW process. Although high arc constriction achieves higher penetration, it also reduces the tolerance of the process to joint gaps and misalignment compared with the broader, conical arc of the GTAW process. The greater complexity of the PAW torch design and the greater number of parts require more scheduled maintenance. The accurate setback of the electrode tip, with respect to the nozzle orifice, is required to maintain consistent results. However, this task is facilitated by a general-purpose tool designed for nozzle removal and replacement and for electrode setback adjustment.

The power source should be of a constant-current design. Transistorized power sources are most common, although inverter power supplies are also available. It should have a minimum open-circuit voltage of 80 V to ensure the reliable initiation and transfer of the main arc current.

Like those of the other arc welding processes, PAW torches are available in a range of sizes for different power ratings and in manual and mechanized versions. The design principles are the same in each case. A tungsten alloy electrode is held in a collet within the torch body. To avoid one of the most common defects in plasma torches, it is critical to hold concentricity between the tungsten electrode and the orifice in the design and manufacture of the torch. The electrode assembly is set inside a plenum chamber, and the plasma gas is supplied to this chamber. A threaded copper alloy nozzle forms the front of this chamber and contains the nozzle orifice that is used to constrict the plasma arc. A shielding gas shroud, usually of an insulating ceramic material, is threaded onto the front end of the torch and surrounds the constricting nozzle, creating an annulus through which the shielding gas is supplied. The torch is connected electrically to the power source, and the electrode forms the negative pole of the circuit for dc welding. The gas hoses that supply the plasma and shielding gases and the water hoses that supply and remove water from the torch are all connected to the torch body or handle. These hoses are enclosed in a flexible sheath that extends from the torch to the components of the welding system. Most constricting nozzles have a single orifice in the center. However, multiple-nozzle orifices can be used with higher-power torches to achieve further arc constriction. The most common version of this type of nozzle has a central orifice flanked by a smaller orifice on each side. The common centerline of the three orifices is arranged at 90° to the weld line during operation.

The nonconsummable electrode employed is usually tungsten with 2% thorium oxide (2% thoriated tungsten). The electrode size is selected according to the welding current level that will be used. The electrode is ground with a tapered point on the end, the angle of which depends on the selected welding current level. The new types of tungsten electrodes, which contain oxides of rare earth elements in place of the thorium oxide, can also be used. These electrodes have been shown to have greater tip life. However, they are more expensive, and their usefulness in PAW may be limited because of the high level of protection provided by the nozzle. In low-current microplasma welding applications, their better emissivity provides easier arc transfer and better overall performance.

The physical configuration of the PAW system requires the use of two gases: a "plasma" or orifice gas and a shielding gas. The primary role of the plasma gas, which exits the torch through the center orifice, is to control arc characteristics and shield the electrode. The shielding gas, introduced around the periphery of the arc, shields or protects the weld area. In many applications, the shielding gas is also partially ionized to enhance the performance of the plasma gas.

Argon is the preferred plasma gas for low-current PAW (<100 A) because of its low ionization potential, which ensures easy and reliable arc starting. Argon-helium mixtures are used for some applications requiring higher heat inputs. The choice of gas used for high-current PAW (≥100 A) also depends on the material to be welded. In almost all cases, the shielding gas is the same as the orifice gas. Again, argon is suitable for welding all metals, but it does not necessarily produce optimum results. Depending on the welding mode used (keyhole or melt-in), the optimal gas blend will vary.

2.7 Plasma-GMAW Welding

Plasma-GMAW arc welding can be defined as a combination of PAW and GMAW within a single torch, where a filler wire is fed through the plasma nozzle orifice. The process can be used for both welding and surfacing. The plasma-GMAW process is suitable for welding a wide variety of materials. The high heat energy supplied by the plasma and gas metal arcs makes the process suitable for high-melting-point materials, such as tungsten and molybdenum. The most common application is welding aluminum sheet and plate. Wear-resistant steels are used with the process in hard-facing applications. Austenitic stainless steels, such as types 308, 309, and 347, as well as nickel alloys, such as alloy 625, are used in cladding applications. Both solid and flux-cored wires can be employed for welding and surfacing, although most applications involve solid wires.

The principles of operation, in terms of equipment, are illustrated in Fig. 2.15. Separate power supplies are used for the PAW and the GMAW elements of the equipment. An arc is struck between the tungsten electrode and the workpiece in a similar fashion to that of a PAW system. The filler wire can be fed to the plasma arc, either with or without the GMAW

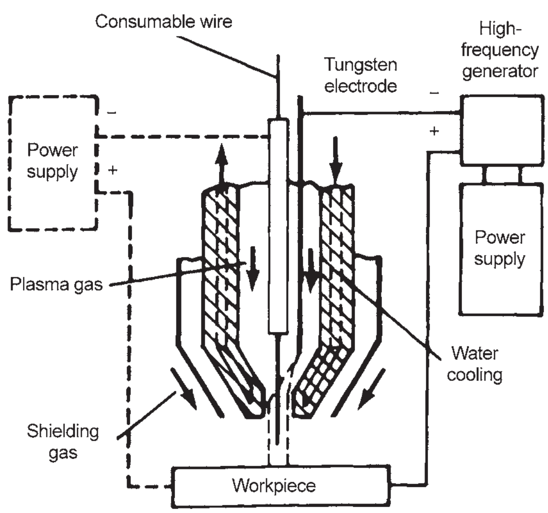

Fig. 2.15 Plasma–gas tungsten arc welding equipment. Source: Ref 2.3

arc established. Without power supplied to the filler wire, the system can be operated as a PAW system with concentric feed of filler wire. Later versions of the system incorporated an annular electrode to replace the offset tungsten electrode in the welding torch.

The equipment can be operated either with a single power source, effectively as a PAW system with concentric filler wire feed, or with two power sources, for the plasma-GMAW operation. The polarity of the tungsten electrode is dc electrode negative (DCEN), as is that of the GMAW part of the system. The heat of the plasma arc is sufficient to achieve good metal transfer stability for the GMAW element, despite the fact that when this process is used separately, it is almost always used in a dc electrode positive (DCEP) mode. The filler wire is heated by the constricted plasma arc, as well as by the cathode heating of its own arc, and by resistance heating along the wire extension. Therefore, the melting and deposition rates of the wire are higher than the rates achieved by heating with either arc alone. Metal transfer is governed not only by plasma streaming but also by arc forces between the wire tip and the workpiece. Because the metal droplets are totally enclosed by the plasma stream, spray transfer takes place even though the GMAW element operates on negative polarity.

The advantages of the plasma-GMAW process include deposition rates and joint completion rates that are higher than those of the conventional GMAW process. Disadvantages include the capital cost of two power sources (although there are systems that are designed to operate with one), greater complexity of the torch, and increased maintenance time and cost associated with this complexity.

2.8 Electroslag and Electrogas Welding

In many respects, the electroslag welding process is similar to the electrogas welding process. The major difference is that electroslag welding is not an arc welding process. The energy for melting and fusing the base metal is provided by a molten bath of slag that is resistance heated by the welding current. However, because of its many similarities with electrogas welding, electroslag welding is described in this section.

Electroslag and electrogas welding are used to weld thick-section materials in the vertical or near-vertical position between retaining shoes. Primarily applied for joining steels thicker than 50 mm (2 in.), electroslag welding involves high energy input relative to other welding processes, resulting in generally inferior mechanical properties, specifically lower toughness of the heat-affected zone (HAZ). However, the high deposition rate and relatively low cost of the process make it attractive for heavy structural fabrication. The properties of electrogas welding, usually applied to steels thinner than 50 mm (2 in.), are generally superior to those of electroslag welds, and the process is commonly applied to the field erection of storage vessels and other less critical structures. A major difference between electroslag and electrogas welding is that the former relies on slag conduction to carry the welding current and the latter uses arc conduction.

Electroslag welding is a vertical welding process producing coalescence with molten slag that melts the filler metal and the surface of the work to be welded. Confined by cooling shoes (Fig. 2.16a), the molten weld pool is shielded by the molten slag, which moves along the full cross section of the joint as welding progresses. The conductive slag is maintained in a molten condition by its resistance to electric current passing between the electrode and the work. Electroslag welding can be considered a progressive melting and casting process in which the heat of a bath of molten flux is used to melt the filler metal and the edges of the plates to be welded. Electric arc occurs only at the beginning of the process, and once a molten bath is achieved, the arc is extinguished. During the process, flux is added periodically or continuously to maintain an adequate slag covering over the pool of molten metal. Two or more retaining shoes hold the molten metal in place until it has solidified. In normal operation with a constant potential power source, the electrode melts off while dipping only partly through the flux bath and gathers in the molten metal pool. In the case of low-carbon steel, the temperature of the bath is reported to be in the vicinity of 1925 °C (3500 °F), while the surface temperature is approximately 1650 °C (3000 °F).

The major process variables are welding current and voltage. Welding current is directly responsible for the electrode melt rate, while voltage influences the base metal penetration and weld bead width. Both variables are sensitive to the physical properties of the welding flux, such as electrical resistivity and fluidity. Direct current constant-voltage power supplies

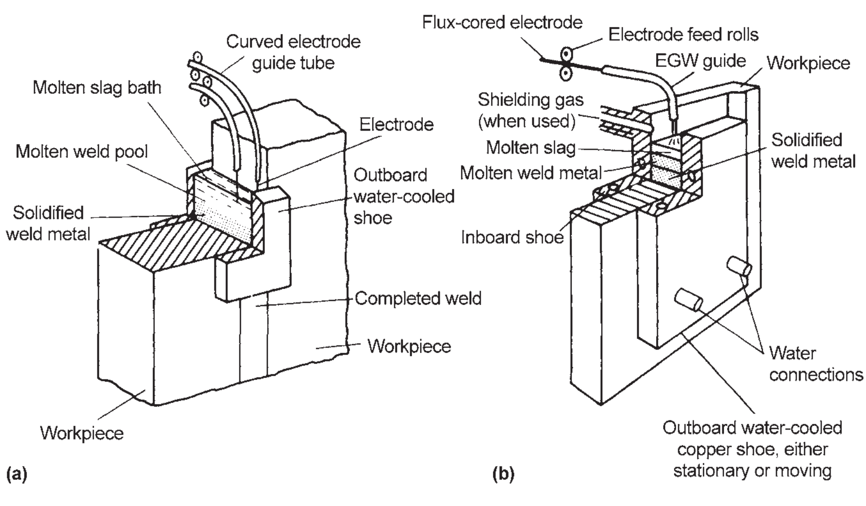

Fig. 2.16 Comparison of primary components of two vertical welding processes in which molten weld pools are confined by cooling shoes: (a) electroslag welding and (b) electrogas welding (EGW). Source: Ref 2.3

are recommended for electroslag welding. For continuous-duty welding, power supplies with adequate current and voltage ratings should be used. Usually, the power rating required is 750 A, 50 V, at 100% duty cycle. A power source of this rating is necessary for each wire in multiwire applications. Constant-current power supplies may be used for electroslag welding; however, they are not recommended for most applications.

Electrode wires are available in two types: solid wire and metal cored wire. Solid wire electrodes similar to those used for GMAW or submerged arc welding are most frequently used. Solid wires used for electroslag welding of low-carbon steel and high-strength low-alloy (HSLA) steel that conforms to AWS specification A5.25/A5.25M (Ref 2.11).

The molten flux is the slag that gives the electroslag process its name. Fluxes are marketed as proprietary materials; there are no standard specifications other than AWS A5.25/A5.25M (Ref 2.11), where fluxes are classified on the basis of the mechanical properties of the weld deposit made with a particular electrode.

Electrogas welding is a GMAW method if a solid wire is used or FCAW method if a tubular wire is used. An external gas is supplied to shield the arc, and molding shoes are used to confine the molten weld metal for vertical position welding (Fig. 2.16b). Electrogas welding may or may not use added flux. In the GMAW method, CO_2 shielding gas is commonly used, and no flux is added. With the FCAW method, the core ingredients provide a small amount of flux to form a thin deposit of slag between the weld and the shoes. Self-shielding electrodes eliminate the need for external shielding gas.

The essential components of equipment for electrogas welding are a power supply, an electrode-wire guide, water-cooled dams, a system for feeding the electrode wire, a mechanism for oscillating the electrode-wire guide, and methods for supplying shielding gas to the area immediately above the weld pool. Except for the power supply, the major components of the equipment are incorporated in an assembly that moves as an integral unit as welding proceeds.

Electrogas welding is done in dc electrode positive (DCEP) current, normally supplied by a transformer-rectifier. Motor-driven and engine-driven generators are sometimes used in field construction sites. The power supply may be of either the constant-current or constant-voltage type; the constant-current type is used for welding units in which vertical travel is controlled by changes in arc voltage.

Either solid or flux-cored electrode wire (filler metal) can be used in electrogas welding. American Welding Society specification A5.26/A5.26M (Ref 2.12) covers the requirements of both types of electrodes for welding carbon and HSLA steels (non-heat-treatable types).

A mixture of approximately 80% Ar and 20% CO_2 is widely used, and is generally preferred, as a shielding gas for most applications. This mixture is well suited for use with both solid and flux-cored electrode wire.

Carbon dioxide alone is also used and is particularly satisfactory when employed with flux-cored wire. Self-shielded flux-cored electrodes contain core materials that generate gases that shield the molten metal from atmospheric contamination.

ACKNOWLEDGMENTS

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CHAPTER 3

Resistance Welding

RESISTANCE WELDING is a group of processes in which the heat for welding is generated by the resistance to the flow of an electrical current through the parts being joined. It is most commonly used to weld two overlapping sheets or plates that may have different thicknesses. A pair of electrodes conducts electrical current to the joint. Resistance to the current flow heats the faying surfaces, forming a weld. The electrodes clamp the sheets under pressure to provide good electrical contact and to contain the molten metal in the joint. The joint surfaces must be clean to obtain consistent electrical contact resistance to obtain uniform weld size and soundness.

The main process variables are welding current, welding time, electrode force, and electrode material and design. High welding currents are required to resistance heat and melt the base metal in a very short time. The time to make a single resistance weld is usually <1 s. For example, welding two pieces of 1.6 mm (1/16 in.) mild steel sheet typical requires a current of approximately 12,000 A and a time of 0.25 s, whereas 3.2 mm (1/8 in.) sheet requires approximately 19,000 A and 0.5 s.

Specific resistance welding processes include:

- Resistance spot welding
- Resistance seam welding
- Projection welding
- Flash welding
- Upset welding

Resistance welding is a low-cost, high-production process widely used in industrial applications. For example, the automotive industry makes extensive use of resistance spot welding processes (Fig. 3.1). It is an excellent substitute for riveted construction of thin metal members.

Fig. 3.1 Robot welding machines are operating in a work cell as part of an automated production line for automobiles. Multiple robots are often used to speed assembly, with each performing a different set of specific welds. Source: Ref 3.1, p 287

3.1 Resistance Spot Welding

Resistance spot welding is a process in which faying surfaces are joined in one or more spots by the heat generated by the resistance to the flow of electric current through workpieces that are held together under force by electrodes. The contacting surfaces in the region of current concentration are heated by a short-time pulse of low-voltage, high-amperage current to form a fused nugget of weld metal. The result of current I flowing through a conductor with resistance R is the production of heat Q given by I^2R in units of watts (which has units of volt-amperes). This is known as joule heating and is the basis for resistance welding. It can essentially increase without limit if the current continues to flow such that the rate of I^2R heating exceeds the rate at which that heat can be dissipated by or from the conductor. For this reason, resistance welding processes are able to cause melting (or fusion) in any metal or alloy and can do so very quickly. When the flow of current ceases, the electrode force is maintained while the weld metal rapidly cools and solidifies. The electrodes are retracted after each weld, which usually is completed in a fraction of a second.

The size and shape of the individually formed welds are limited primarily by the size and contour of the electrode faces. The weld nugget forms at the faying surfaces (Fig. 3.2) but does not extend completely to the outer surfaces. In a cross section, the nugget of a properly formed spot weld is oblong or oval in shape. In a plan view, it has the same shape as the electrode face (which usually is round) and approximately the same

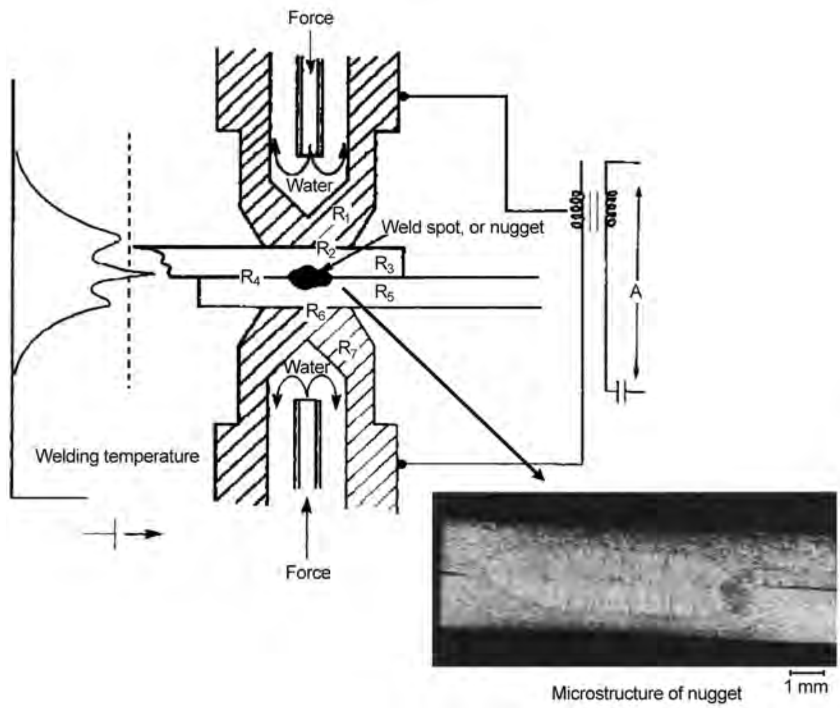

Fig. 3.2 Setup for resistance spot welding. Cross section shows shape and position of nugget relative to inner and outer surfaces of workpieces. Source: Ref 3.2, Ref 3.3

size. The spots should be located a sufficient distance from the edge of the workpiece (edge distance) so that there is enough base metal to withstand the electrode force and to ensure that the local distortion during welding does not allow expulsion of metal from the weld.

Spot welding is the most widely used joining technique for the assembly of sheet metal products such as automotive body assemblies, appliances, furniture, and building products. Many assemblies of two or more sheet-metal stampings that do not require gas-tight or liquid-tight joints can be more economically joined by high-speed spot welding than by mechanical methods. Containers are frequently spot welded. The attachment of braces, brackets, pads, or clips to formed sheet-metal parts such as cases, covers, bases, or trays is another common application of spot welding.

Major advantages of spot welding include high operating speeds and suitability for automation or robots and inclusion in high-production assembly lines together with other fabricating operations. With automatic control of current, timing, and electrode force, sound spot welds can be produced consistently at high production rates and low unit labor costs using semiskilled operators. Most metals can be resistance spot welded if the appropriate equipment is used with suitable welding conditions. This is particularly true for thin sheet or strip steel products, whether uncoated or coated. Table 3.1 provides a guide for spot welding of various metal combinations.

Parts of widely different thicknesses may be spot welded. For example, 0.4 mm (1/64 in.) material can be welded to a 150 mm (6 in.) thick piece and would require only slightly more power input and pressure than to weld two pieces of 0.4 mm (1/64 in.) material, because it is not necessary to heat the 150 mm (6 in.) piece through, and the push-up is obtained on the thinner piece. The thickness of the thinner component is referred to as the *governing metal thickness* because it dictates the heat input. However, the thermal mass of the larger component may make spot welding applications impractical because the thick section may not reach fusion temperature before the thin piece is melted. The limit to welding pieces of equal thickness with an uninterrupted flow of current seems to be approximately 3.2 mm (1/8 in.). Greater thicknesses may be welded by a technique known as pulsation welding, in which current is turned off during the weld at intervals that allow the electrodes to cool the electrode/workpiece surface. This ensures that the heat will be generated as desired, primarily at the faying surfaces.

The equipment needed for spot welding can be simple and inexpensive or complex and costly, depending on the degree of automation. Spot welding machines consist of three principal elements:

- Electrical circuit, which consists of a welding transformer, tap switch, and a secondary circuit

Table 3.1 Relative weldability ratings of selected metal and alloy combinations used for resistance spot welding operations

Metals	Aluminum	Stainless steel	Brass	Copper	Galvanized iron	Steel	Lead	Monel	Nickel	Nichrome	Tinplate	Zinc	Phosphor bronze	Nickel silver	Terneplate
Aluminum	B	E	D	E	C	D	E	D	D	D	C	C	C	F	C
Stainless steel	F	A	E	E	B	A	F	C	C	C	B	F	D	D	B
Brass	D	E	C	D	D	D	F	C	C	C	D	E	C	C	D
Copper	E	E	D	F	E	E	E	D	D	D	E	E	C	C	E
Galvanized iron	C	B	D	E	B	B	D	C	C	C	B	C	D	E	B
Steel	D	A	D	E	B	A	E	C	C	C	B	F	C	D	A
Lead	E	F	F	E	D	E	C	E	E	E	...	C	E	E	D
Monel	D	C	C	D	C	C	E	A	B	B	C	F	C	B	C
Nickel	D	C	C	D	C	C	E	B	A	B	C	F	C	B	C
Nichrome	D	C	C	D	C	C	E	B	B	A	C	F	D	B	C
Tinplate	C	B	D	E	B	B	...	C	C	C	C	C	D	D	C
Zinc	C	E	E	E	V	F	C	F	F	F	C	C	D	F	C
Phosphor bronze	C	D	C	C	D	C	E	C	C	D	D	D	B	B	D
Nickel silver	F	D	C	C	E	D	E	B	B	B	D	F	B	A	D
Terneplate	C	B	D	E	B	A	D	C	C	C	C	C	D	D	B

A, excellent; B, good; C, fair; D, poor; E, very poor; F, impractical. Source: Ref 3.4

- Control circuit, which initiates and times the duration of current flow and regulates the welding current
- Mechanical system, which consists of the frame, fixtures, and other devices that hold and clamp the workpiece and apply the welding force

Specifications for resistance welding equipment have been standardized by the Resistance Welder Manufacturers Association, and specifications for controls are issued by the National Electric Manufacturers Association.

Single-spot welds are usually made by direct welding. Three arrangements used for making this type of weld are shown in Fig. 3.3. In all three arrangements, one transformer secondary circuit makes one spot weld. The simplest and most common arrangement is two workpieces sandwiched between opposing upper and lower electrodes (Fig. 3.3a). A conductive plate or mandrel having a large containing surface can be used as the lower electrode (Fig. 3.3b); this reduces marking on the lower workpiece and conducts heat away from the weld more rapidly and may be necessary because of the shape of the workpiece. A conductive plate or mandrel beneath the lower workpiece can also be used in conjunction with a second upper electrode (Fig. 3.3c).

In both direct and series multiple-spot welding (Fig. 3.4), tip contour and surface condition must be the same for each electrode. Also, the force exerted by all the electrodes on the workpieces must be equal, regardless of inequalities in work-metal thickness. The force can be equalized by using a spring-loaded electrode holder or a hydraulic equalizing system. Two arrangements of the secondary circuit for making two or more spot welds simultaneously by direct welding are shown in Fig. 3.4(a) and (b). The use of a conductive plate or mandrel (Fig. 3.4b) minimizes weld marks on the lower workpiece.

Three arrangements for making a number of spot welds simultaneously by series welding are shown in Fig. 3.4(c) to (e). In Fig. 3.4(d), each of the two transformer secondary circuit makes two spot welds. A portion of the current bypasses the weld nuggets through the upper workpiece. Figure 3.4(e) is commonly referred to as *push-pull welding*. The advantage to this process is that the secondary loop area is quite small. This is common for

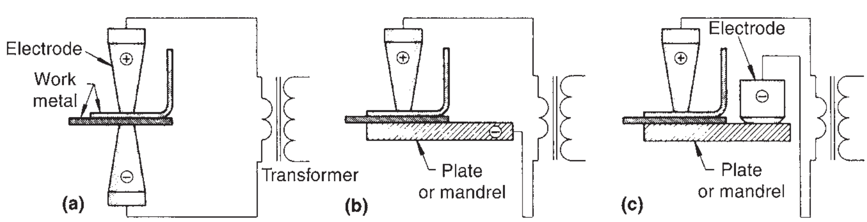

Fig. 3.3 Relation of work metal to electrodes when making single-spot welds by direct welding. Source: Ref 3.4

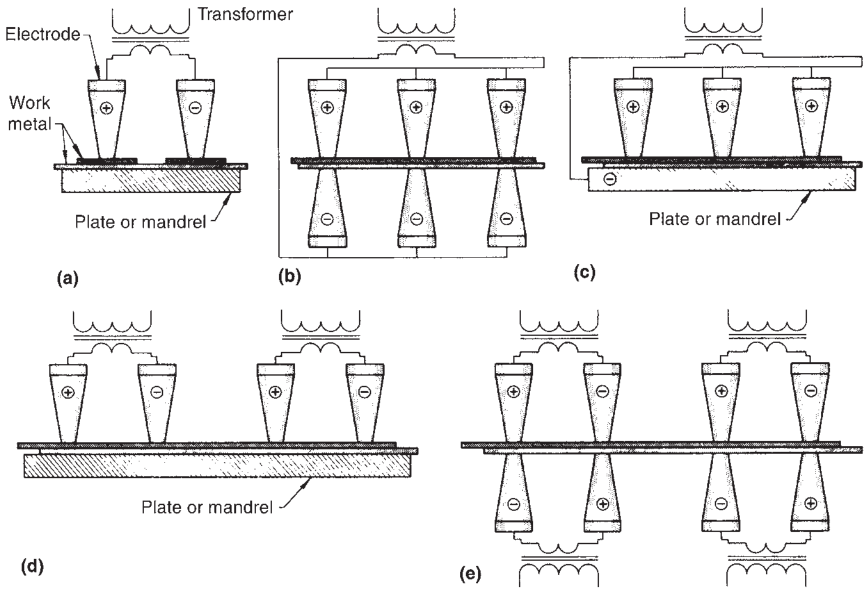

Fig. 3.4 Relation of work metal to electrodes when making multiple-spot welds: (a) and (b) direct welding; (c), (d), and (e) series welding. Source: Ref 3.4

components such as floor pans where a normal welding unit would have a throat several feet deep.

3.2 Resistance Seam Welding

Resistance seam welding is a process in which heat caused by resistance to the flow of electric current in the work metal is combined with pressure to produce a welded seam. This seam, consisting of a series of overlapping spot welds, is normally gas-tight or liquid-tight. Two rotating, circular electrodes (electrode wheels), or one circular and one bar-type electrode, are used for transmitting the current to the work metal. When two electrode wheels are used, one or both wheels are driven either by means of a gear-driven shaft or by a knurl or friction drive that contacts the peripheral surface of the electrode wheel. The series of spot welds is made without retracting the electrode wheels or releasing the electrode force between spots, although the electrode wheels may advance either continuously or intermittently.

Advantages of seam welding, compared with resistance spot welding, projection welding, and laser welding, are:

- Gas-tight or liquid-tight joints can be produced (not possible with spot welding or projection welding).

- Seam width may be less than the diameter of spot welds, because the electrode contour can be continuously dressed and is therefore of a stable shape.
- High-speed welding (especially on thin stock) is possible.
- Tooling cost is generally favorable per inch of flange welded.
- Coated steels are generally more weldable using seam welding than spot welding, because coating residue can be continuously removed from the electrode wheels if special provisions are made.
- Coated steels are generally more weldable using seam welding than laser welding, because coating volatility is minimized by the intense pressure field in the weld zone
- Resistance seam welding is not particularly fit-up sensitive compared with laser welding. The hardness of resistance seam welds made with air cooling is less than that of laser welds (120 HV vs. 250 HV, respectively, for drawing-quality bare steel, and 170 HV vs. 300 HV, respectively, for organic-coated drawing-quality steel).

Limitations of seam welding, apart from those it shares with spot welding and projection welding, are:

- Welds must ordinarily proceed in a single plane or on a uniformly curved surface. For special cases, multiplane welding has been achieved using a tilting welding head. The radius of curvature connecting the planes must be sufficiently large.
- Obstructions along the path of the electrode wheel must be avoided or compensated for in the design of the wheel.
- Material handling must not induce extraneous forces into the fragile, molten weld zone during welding.
- The length of seams made in a longitudinal seam welding machine is limited by the throat depth of the machine. Current shunting through the weld, or a change in electrical impedance caused by the movement of the product inside the throat of the machine, can require current compensation as welding proceeds.
- Components using multiple crossing seam welds can be quality sensitive at the weld intersections.
- External water cooling of the electrodes and the weld zone may be required for high-speed welding. (Under high-speed conditions the weld nuggets are still molten as they leave the pressure field of the wheels.) External cooling may add tooling cost for water containment and water removal from the parts after welding.
- Materials requiring postweld heat and temper should not be seam welded without special considerations.
- Chromates and insulating lacquer coatings are not resistance seam weldable.

Low-carbon, high-carbon, low-alloy, high-strength low-alloy (HSLA), stainless, and many coated steels can be resistance seam welded satisfactorily. Alloys with carbon levels above about 0.15% may tend to form areas of hard martensite upon cooling. In critical applications, these welds may require postweld tempering to reduce the hardness and brittleness. In some cases, this can be done in the welding machine. Tempering can also be done in a furnace or by induction heating. Nonferrous alloys commonly resistance seam welded include aluminum and aluminum alloys and nickel and nickel alloys. Seam welding is not recommended for copper and high-copper alloys.

A seam welding machine is similar in construction to a spot welding machine, except that one or two electrode wheels are substituted for the spot welding electrodes. Generally, seam welding is done in a press-type resistance welding machine. There are four basic types of machines:

- *Circular:* Axis of rotation of the electrode wheels is at right angles to the front of the machine (Fig. 3.5a).
- *Longitudinal:* Axis of rotation of the electrode wheels is parallel to the front of the machine (Fig. 3.5b), and throat depth is typically 305 to 915 mm (12 to 36 in.).
- *Universal:* A swivel-type head and interchangeable lower arms allow the axis of rotation of the electrode wheels to be set either at right angles or parallel to the front of the machine.
- *Portable:* Work is clamped in a fixture, and a portable welding head is moved over the seam. This type of machine is used for workpieces that are too bulky to be handled by regular machines.

Electrode wheels range in diameter from 50 to 610 mm (2 to 24 in.). Narrower wheels are used in machines with knurl or friction drive; wider

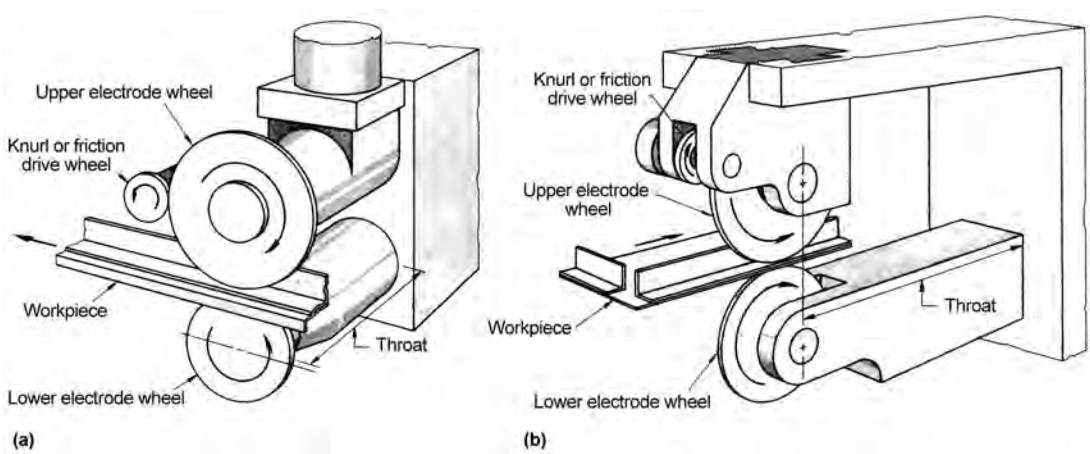

Fig. 3.5 Position of electrode wheels on seam welding machines: (a) circular machine and (b) longitudinal machine. Source: Ref 3.4

wheels, in gear drive and idler machines. A small-diameter electrode wheel (Fig. 3.6a) or a large-diameter wheel mounted on a canted axis (Fig. 3.6b) can be used to avoid interference with a sidewall when a narrow flange is being welded on an inside radius or on a reentrant curve. Beads, ribs, and other extensions on the surfaces to be seam welded can be passed over by cutting notches in the electrode wheels.

3.3 Projection Welding

Projection welding is a resistance welding process in which current flow and heating are localized at a point or points predetermined by the design or shape of one or both of two parts to be welded (Fig. 3.7). The

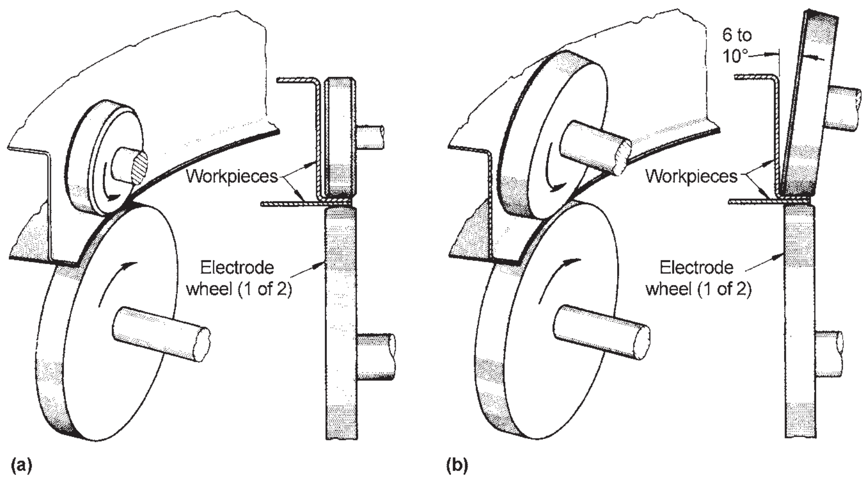

Fig. 3.6 Upper electrode wheels used to avoid interference with a sidewall: (a) small-diameter wheel and (b) canted, large-diameter wheel. Source: Ref 3.4

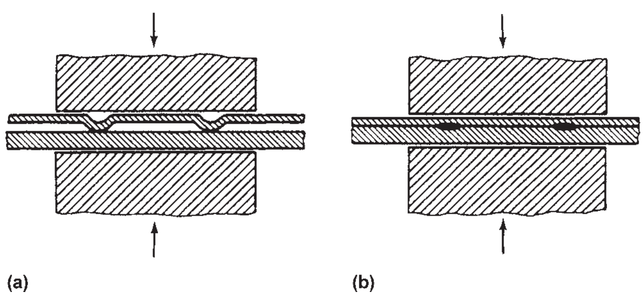

Fig. 3.7 Relation of weld nuggets to embossed regions of metal sheets used in projection welding: (a) electrical circuit loop is completed when current travels through embossed projection contact points; (b) addition of pressure after welding current is turned off causes plastic deformation that flattens the projections. Source: Ref 3.4

process is closely related to spot welding, in which current flow and heating are localized by one or both electrode contact faces, which determine the location, size, and shape of the weld produced.

Projections may be of any practical shape that can properly concentrate the welding current. In cross-wire projection welding, the curved surfaces of two intersecting wires perform the function of a projection. The shapes of parts may also take the place of conventional projections in projection welding of special types of joints. The formation of a projection weld nugget, which depends on the design of the projection, the selection of welding conditions, and the adequacy of the resistance welding equipment, is shown in Fig. 3.8. In this application, 2.33 mm (0.092 in.) thick low-carbon steel is projection welded using embossed spherical projections and a weld time of 20 cycles (1/3 s).

In the first stage of welding (Fig. 3.8a), the workpieces are brought together under pressure without application of welding current, and the projection may be slightly compressed and indented into the surface of the mating workpiece. At about 20% of weld time (heat time), collapse of the projection is nearly complete and a pressure weld is formed (Fig. 3.8b). A nugget of fused weld metal does not begin to form until about 50% of the weld time has elapsed. At about 60 to 70% of weld time, fusion has progressed a sufficient distance from the interface to produce a well-defined weld nugget that has about half its final thickness (penetration) and diameter (Fig. 3.8c). Sheet separation adjacent to the weld nugget has been reduced to zero, and the softened metal above the nugget has been flattened against the face of the upper electrode (compare with Fig. 3.8b). Nugget diameter, penetration, and shear strength continue to increase as weld time progresses. Figure 3.8(d) shows the fully developed weld nugget.

Projection welding is used where there is a high thickness ratio (e.g., nuts welded to sheet) and where the appearance of the sheets must be

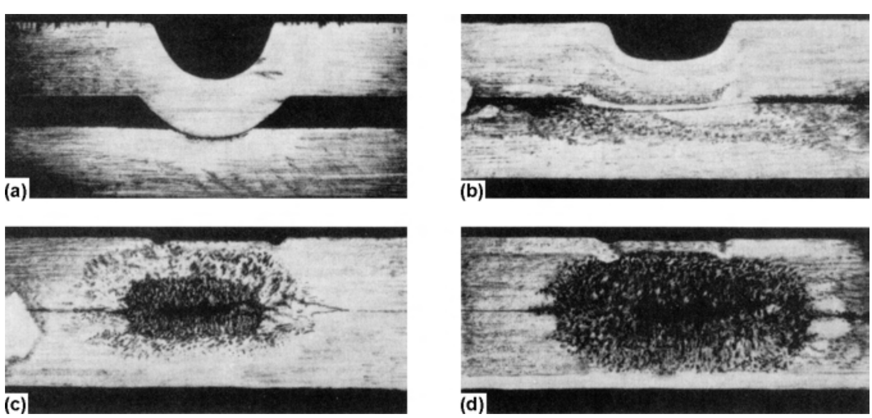

Fig. 3.8 Development of weld nugget during projection welding of embossed spherical projections. Source: Ref 3.4

controlled (e.g., appliance surfaces). The principal application of projection welding is the joining of stamped low-carbon, low-alloy, and HSLA steel parts. During stamping (punching, drawing, or forming), one of the parts must have a projection that has been formed during the stamping operation to enable projection welding. Projection welding is also used for joining screw-machine parts to stamped parts; the projection is machined or cold formed on the end of the screw-machine part.

Projection welding is most successful in workpieces 0.56 to 3.18 mm (0.022 to 0.125 in.) thick. Stock as thin as 0.25 mm (0.010 in.) thick has been projection welded; however, projection design is critical, and machines with low-inertia heads and fast follow-up are needed. Sections less than 0.25 mm (0.010 in.) thick are more adaptable to spot welding.

The principal advantages of projection welding are:

- The number of welds that can be made simultaneously with one operation of the welding machine is limited only by the ability of the controls to regulate current and force.
- Because of greater current concentration at the weld, and thus less chance of shunting, narrower flanges can be welded, and welds can be spaced closer together by projection welding than by spot welding.
- Electrodes used in projection welding have faces larger than the projections and larger than the faces of electrodes used for making spot welds of comparable nugget diameter. Consequently, because of lower current density, electrodes require less maintenance than do spot welding electrodes.
- Projection welds can be made in metal that is too thick to be joined by spot welding.
- Flexibility in selection of projection size and location allows welding of workpieces in thickness ratios of ≥6 to 1. Workpieces in thickness ratios ≥3 to 1 sometimes are difficult to spot weld.
- The process can be used to make leak-proof joints (e.g., ring projections).

Limitations of projection welding include:

- Forming of one or more projections on one of the workpieces may require extra operations unless the parts are press formed to design shape.
- When several welds are made at once with the same electrode, alignment of the work and dimensions (particularly height) of the projections must be held to close tolerances to obtain consistent weld quality.
- When making simultaneous projection welds, the projection layout will be dictated by the shunt current paths, which may not coincide with the desired location.

Press-type machines, with either single-phase or three-phase transformers, usually are used for projection welding. The welding head in these machines is guided by bearings or ways and moves in a straight line. Platens with T-slots or tapped holes are used for mounting the welding dies or electrodes. Rocker-arm machines generally are not used for projection welding because the electrode moves in an arc that can cause slippage between the components as the projection collapses.

The major variables that affect projection welding are welding current, electrode force, and weld time. Welding current required for projection welding, although slightly less per weld than that needed for spot welding, must be high enough to cause fusion before the projection is completely flattened. The recommended current is the highest current that, when used with the current electrode pressure, does not cause excessive expulsion of metal.

Electrode force used in projection welding depends on the work metal, the size and design of the projection, the number of projections in the joint, and the welding machine. Excessive force causes the projections to collapse before the weld area has reached the proper temperature, resulting in the formation of ring welds, in which fusion occurs around the periphery of the projection but is incomplete at the center. For best weld appearance, the electrode force should be such that the projection is flattened completely after the metal has reached welding temperature.

Weld time for a given type and thickness of work metal depends on welding current and rigidity of the projection. Weld time is less important than electrode force in projection welding of low-carbon, low-alloy, and HSLA steel, provided that the time is sufficient to produce a nugget of adequate size at the chosen welding current. A short weld time creates higher production efficiency and less discoloration and distortion of the workpiece. After the proper electrode force and welding current are determined, the weld time is adjusted to make the desired weld.

3.4 Flash Welding

Flash welding is used to join sections of metals and alloys in production quantities. It is a resistance/forge welding process in which the items to be welded are securely clamped to electric current-carrying dies, heated by the electric current, and upset (Fig. 3.9). Clamping ensures good electrical contact between the current-carrying dies and the workpiece and prevents the parts from slipping during the upsetting action. Flash welding equipment must be durable to withstand high clamping force and upset pressures without deflecting. If deflection occurs, misalignment of workpieces may occur during welding. Flash welding is rapid and economical and, when properly executed, produces welds of uniform high quality. A typical flash welding machine comprises a horizontal press-transformer com-

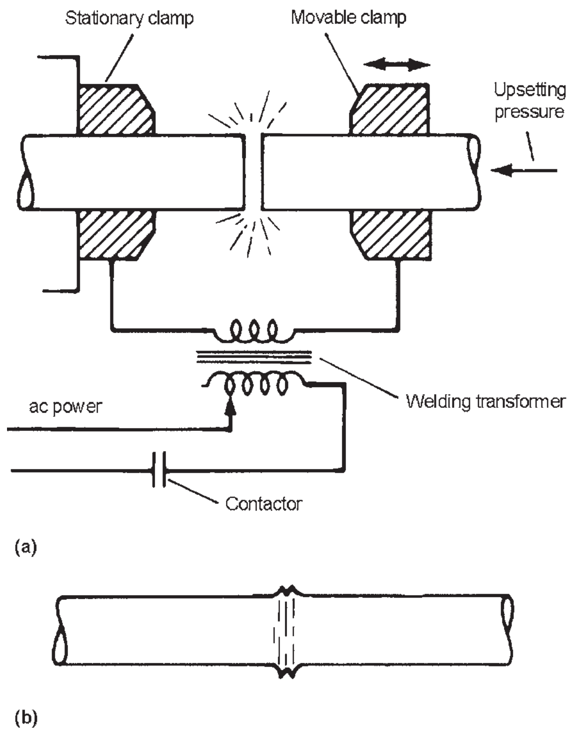

Fig. 3.9 Weld produced when using the flash welding process: (a) workpieces securely clamped in current-carrying dies before upsetting operation is initiated; (b) finished weld produced after upsetting operation. Source: Ref 3.4

bination with conducting work-clamping dies mounted on the press platens.

Flash welding can be used for joining many ferrous and nonferrous alloys and combinations of dissimilar metals. In addition to low-carbon steels, metals that are flash welded on a production basis include low-alloy steels, tool steels, stainless steels, aluminum alloys, magnesium alloys, nickel alloys, and copper alloys. Parts that are flash welded come in a variety of forms, including forgings, rolled or extruded bar, sheet, strip, or plate, ring preforms, and castings.

Fundamentally, flash welding involves heating the ends of the pieces to be welded and subsequently forging them together. After the parts are clamped in the welding machine and the welding power is activated, the abutting surfaces are brought together for a brief period of violent flashing. This phase of the welding sequence is called burnoff. It serves the function of squaring off the abutting surfaces and compensates for inconsistencies in end preparation. The primary purpose of flashing is to generate enough heat to produce a plastic zone that permits adequate upsetting. The rate of energy input must be in proper proportion to the travel of the platen or movable die, so that constant flashing is maintained until the appropriate amount of metal is flashed off and the required plastic zone is obtained.

During the heating phase, a thermal distribution pattern is established along the axial length of the pieces being joined, which is characterized by a steep temperature gradient. The major difference between the temperature pattern developed in flash welding and that developed in resistance welding is that flash welding produces a much steeper thermal gradient. This steep thermal gradient, combined with the resulting characteristic upset pattern, enables flash welding to accommodate a much greater variety of materials and shapes than can be welded by resistance welding. Once the proper temperature-distribution pattern has been established, the abutting surfaces are rapidly forced together. The parts must be securely held together during the forging process to prevent slipping. Three distinct peaks are characteristic of flash welds (Fig. 3.10). The two peaks on either side of the weld line represent the material displaced by the upsetting action; the center peak is the molten metal extruded out of the weld, including oxides or contaminants formed during heating.

Welding takes place during the upsetting action, and some metal must be extruded from the weld zone to remove slag and other inclusions not expelled during flashing. The extruded metal must extend beyond the cross-sectional boundaries of the workpiece to ensure that maximum amounts of slag and inclusions are removed when the weld upset is removed during subsequent trimming. When the weld upset is removed, no evidence of the weld should remain. Porosity near the outer surface on an etched section of the weld, or a crevice around the workpiece after the weld upset has been removed, indicates incomplete bonding because of either insufficient upsetting force or insufficient plasticity during upsetting.

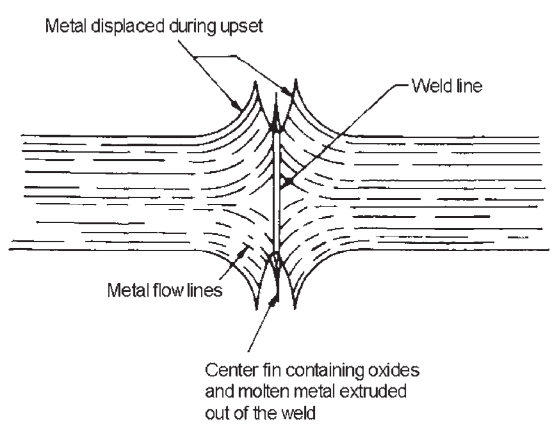

Fig. 3.10 Cross-sectional view of typical peaks and flow lines generated in a flash weld. Source: Ref 3.4

One of the major considerations for flash welding is the electrical power service. *Flashing* is a term used to describe the major heating process during flash welding. When the ends of the workpiece are brought together under light pressure, an electrical short circuit is established through the material. Because the abutting surfaces are not perfectly matched, the short-circuited current flows across the joint only at a few small contact areas. The large amount of current flowing through a relatively small area causes very rapid heating to the melting point. Heating is so rapid and intense that molten metal is expelled explosively from the joint area. After this expulsion, a brief period of arcing occurs. Arcing is not sustained due to the low voltages employed.

After the expulsion of molten metal and subsequent arcing, small craters are formed on the ends of the abutting surfaces. The pieces are steadily advanced toward one another, and other short circuits are formed and additional molten metal is expelled (Fig. 3.11). This process continues as random melting, arcing, and expulsion occur over the entire cross-sectional surface. During flashing, many active areas are in various stages of this sequence. Flashing surfaces act as heat sources, and the steep thermal profile is established primarily from these heat sources. Temperatures of the flashes are at or above the melting point of the material and are progressively lower as distance progresses from the flashing surface toward the clamp. Parts to be welded must be clamped or fixtured securely

Fig. 3.11 Massive arcing and expulsion during flash welding

to provide good electrical contact with current-carrying dies and to transmit the upset forces. Also, a reliable source of force for the upsetting action is required.

Flash welding machines may be manual, semiautomatic, or fully automatic. Machines used for flash welding generally consist of:

- A mainframe
- A low-impedance welding transformer
- A stationary platen
- A movable platen on which clamping dies, electrodes, and other tools needed to position and hold the workpieces are mounted
- Flashing and upsetting mechanisms
- The necessary electrical, air, or hydraulic controls.

Workpieces must be accurately clamped to maintain alignment, to allow the secondary current to pass into the workpieces, and to apply the upsetting force properly. Generally, the parts of the clamping mechanism that actually grip the workpiece are the electrodes, often called clamping dies.

3.5 Upset Welding

As shown in Fig. 3.12, upset welding is a resistance welding process using both heat and deformation to form a weld. The heat is produced by

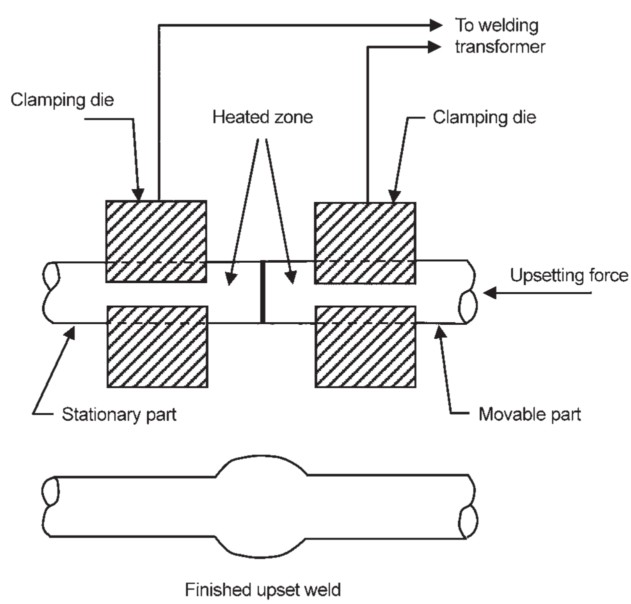

Fig. 3.12 General arrangement for upset welding of bars, rods, and pipes. Source: Ref 3.5, p 598

resistance to the flow of electrical current at the interface of the abutting surfaces to be joined. The deformation results from force on the joint in combination with softening from the electrical resistance heat. Upset welding typically results in solid-state welds (no melting at the joint). The deformation at the weld joint provides intimate contact between clean adjoining surfaces, allowing formation of strong metallurgical bonds. If any melting does occur during upset welding, the molten metal is typically extruded out of the weld joint area.

A wide variety of shapes and materials can be joined using upset welding in either a single-pulse or continuous mode. Wire, bar, strip, and tubing can be joined end to end with a single pulse of welding current. Seams on pipe or tubing can be joined using continuous upset welding by feeding a coiled strip into a set of forming rolls, resistance heating the edges with wheel electrodes, and applying a force to upset the edges together.

Equipment for single-pulse upset welding is relatively simple. It consists of a pneumatic or hydraulic system for force application, transformers or a bank of diodes as a source of electrical current, and a standard resistance welding controller. A data acquisition system usually is employed to record the force, current, voltage, and motion of the weld head during welding. Equivalent welds have been made using both alternating and direct current.

Upset welds have characteristics similar to those of inertia friction welds, which are also solid-state welds. The amount of deformation is usually less for upset welds, and the deformation can be more precisely controlled. For example, a pipe butt weld made using inertia friction welding will have a large upset on both the inside and outside, whereas an upset weld can be controlled, through joint design and welding parameters, to have essentially no internal upset.

ACKNOWLEDGMENTS

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CHAPTER 4

Other Fusion Welding Processes

THE OTHER fusion welding processes that were not covered in Chapters 2 and 3 in this book are covered in this chapter: oxyfuel gas welding, oxyacetylene braze welding, stud welding (stud arc welding and capacitor discharge stud welding), high-frequency welding, electron beam welding, laser beam welding, hybrid laser arc welding (HLAW), and thermit welding.

4.1 Oxyfuel Gas Welding

Oxyfuel gas welding is a manual process in which the metal surfaces to be joined are melted progressively by heat from a gas flame, with or without filler metal, and are caused to flow together and solidify without the application of pressure to the parts being joined. The most important source of heat for oxyfuel gas welding is the oxyacetylene welding torch.

The simplest and most frequently used oxyfuel gas welding system consists of compressed gas cylinders, gas pressure regulators, hoses, and a welding torch. Oxygen and fuel are stored in separate cylinders. The gas regulator attached to each cylinder, whether fuel gas or oxygen, controls the pressure at which the gas flows to the welding torch. At the torch, the gas passes through an inlet control valve and into the torch body, through a tube or tubes within the handle, through the torch head, and into the mixing chamber of the welding nozzle or other device attached to the welding torch. The mixed gases then pass through the welding tip and produce the flame at the exit end of the tip. This equipment can be mounted on and operated from a cylinder cart, or it can be a stationary installation. Filler metal, when needed, is provided by a welding rod that is melted progressively along with the surfaces to be joined.

Oxyfuel gas welding can be used to join thin carbon steel sheet and carbon steel tube and pipe. The advantages of oxyfuel gas welding include the ability to control heat input, bridge large gaps, avoid melt-through, and clearly view the weld pool. Carbon steel sheet, formed in a variety of shapes, often can be welded more economically by oxyfuel gas welding than by other processes. Oxyfuel gas welding is capable of joining small-diameter carbon steel pipe (up to about 75 mm, or 3 in., in diameter) with resulting weld quality equal to competitive processes and often with greater economy. Pipe with wall thickness up to 4.8 mm (3/16 in.) can be welded in a single pass.

Oxygen and acetylene are the principal gases used in oxyfuel gas welding. Oxygen supports combustion of the fuel gases. Acetylene supplies both the heat intensity and the atmosphere needed to weld steel. Hydrogen, natural gas, propane, and proprietary gases are used only to a limited extent in oxyfuel gas welding or brazing of metals with a low melting temperature. Only by burning selected fuel gases with high-purity oxygen in a high-velocity flame can the high heat transfer intensity required in oxyfuel gas welding be obtained. Oxygen is supplied for oxyfuel gas welding and cutting at a purity of ≥99.5%, because small percentages of contaminants have a noticeable effect on combustion efficiency. When the consumption requirement is relatively small, the oxygen is supplied and stored as a compressed gas in a standard steel cylinder under an initial pressure of up to 180 MPa (26 ksi). The most frequently used cylinder (Fig. 4.1) has a capacity of 6.91 m^3 (244 standard cubic feet). A standard cubic foot (scf) of gas is defined as equivalent to 0.028 m^3 (1 ft^3) of gas at 20 °C (70 °F) and 100 kPa (1 atm, or 14.7 psi) pressure. This definition, which is used in the gas industry and some engineering practice, differs from the standard temperature and pressure of 0 °C (32 °F) and 100 kPa (1 atm) used in scientific work.

Acetylene is a hydrocarbon gas with the chemical formula C_2H_2. When under pressure of ≥203 kPa (29.4 psi), acetylene is unstable, and a slight shock can cause it to explode, even in the absence of oxygen or air. Safety rules for the use of acetylene and the handling of acetylene equipment are extremely important. Acetylene should not be used at pressure >105 kPa (>15 psi). Acetylene generators for on-site gas production are constructed so that the gas is not given off at pressures much greater than 105 kPa (15 psi). Commercially supplied portable cylinders are specially constructed to store acetylene under high pressure.

The general construction of an oxyfuel gas welding torch is shown schematically in Fig. 4.2. Welding torches control the operating characteristics of the welding flame and enable the flame to be manipulated during welding. The choice of torch size and style depends on the work to be performed. Aircraft welding torches, for example, are small and light to permit ease of handling. Most torch styles permit one of several sizes of welding tips or a cutting attachment to be added.

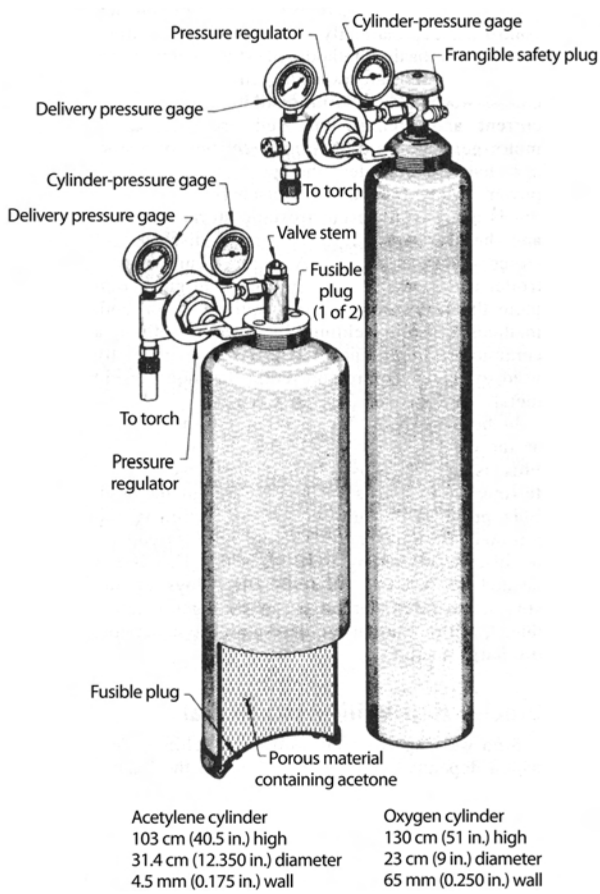

Fig. 4.1 Gas cylinders and regulators used in oxyfuel gas welding. Source: Ref 4.1

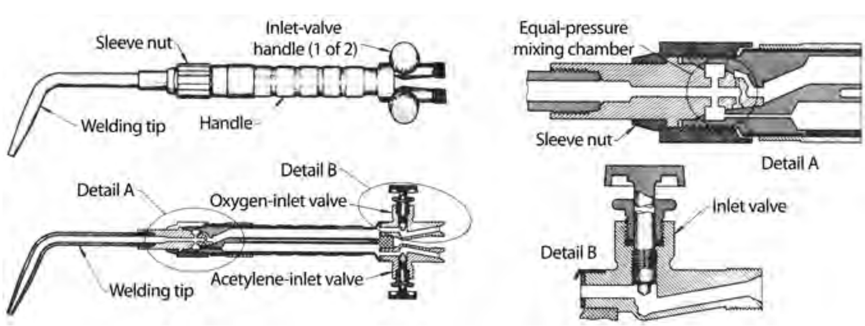

Fig. 4.2 Oxyfuel gas welding torch. Source: Ref 4.1

Different welding atmospheres and flame temperatures can be produced by varying the relative amounts of oxygen and fuel gas in the gas flowing to the tip of the torch. Usually, a welder makes the appropriate adjustments in gas flow based on the appearance of the flame. This is not true for oxyhydrogen welding, however. For all fuels, the oxyfuel flame can be classified as reducing, neutral, or oxidizing.

Reducing Flame. If oxygen is insufficient for full combustion, the flame is known as a reducing flame. It is frequently used for welding with low-alloy steel rods. The flame temperature at the tip of the inner cone is about 2930 to 3040 °C (5300 to 5500 °F).

Neutral Flame. In the neutral flame, the oxygen-to-acetylene ratio is 1 to 1 (more accurately, 1.1 to 1), and the temperature at the tip of the inner cone is probably >3040 °C (>5500 °F). The neutral flame is ideal for the welding of steel, and it is also needed when the presence of carbon must be strictly avoided. When the oxidizing condition is unacceptable, as in welding stainless steel, the use of a neutral flame is essential for good results.

Oxidizing Flame. A flame with excess oxygen is known as an oxidizing flame. An oxidizing flame should never be used in welding steel. It is used only in welding copper and certain copper-based alloys, and the flame should be sufficiently rich in oxygen to ensure that a film of oxide slag forms over the weld to provide shielding for the weld pool. With oxygen-to-acetylene ratios of about 1-3/4 to 1, flame temperature can approach 3315 °C (6000 °F).

Filler metal for oxyfuel gas welding of low-carbon steel is available in the form of cold-drawn steel rods 915 mm (36 in.) long and 1.6 to 4.0 mm (1/16 to 5/32 in.) in diameter. Welding rods for oxyfuel gas welding of other metals are supplied in various lengths, depending on whether they are wrought or cast. Steel welding rods have been standardized in American Welding Society specification A5.2/A5.2M (Ref 4.2). This specification contains three classifications of welding rods based on the minimum tensile strength of all-weld-metal and transverse weld test specimens.

4.2 Oxyacetylene Braze Welding

Oxyacetylene braze welding is a method of oxyfuel gas welding capable of joining many base metals, but it is used primarily on steel and cast iron with a copper alloy filler metal (rod) and a flux. Braze welding is similar to torch brazing with a filler rod, except that joint openings are wider and distribution of filler metal takes place by deposition rather than by capillary action. Equipment and some filler metals used in braze welding are the same as those used in torch brazing. In braze welding of ferrous metals, the base metal is not melted. The filler-to-base-metal bond is the same as in torch brazing. Flux is applied to the joint surfaces, which, together with the surrounding area, are preheated to the point where the filler metal wets or "tins" these surfaces.

Braze welding is used for making groove, fillet, plug, or slot welds in metal ranging from thin sheet to heavy castings. Weld layers can be built up, as in oxyfuel gas welding. The process is often used as a low-temperature substitute for oxyfuel gas welding. Braze welding resembles brazing in that nonferrous filler metals are used, and bonding is achieved without melting the base metal. Braze welding resembles welding because it can be used for filling grooves and for building up fillets as required.

4.3 Stud Arc Welding

Stud arc welding, also known as arc stud welding, is a commonly used method for joining a metal stud, or fastener, to a metal workpiece. The process has been used as a metal fastening method since the 1940s. Millions of specially designed and manufactured metal studs are welded by this process every week in such diverse industries as construction, shipbuilding, automotive, and hard goods, as well as in miscellaneous industrial applications. The stud welding process represents an alternative to other welding processes and is also a substitute for other fastening procedures, such as drilling and tapping, bolting, and self-tapping screws.

There are two basic types of stud arc welding, which are differentiated by the source of welding power. One type uses direct current (dc) power provided by a transformer/rectifier or a motor generator similar to that used in the shielded metal arc welding process. The second type uses power discharged from a capacitor storage bank. The process based on a dc power source is known as stud arc welding, whereas the process that uses capacitors is known as capacitor discharge stud welding.

Both the stud arc welding and capacitor discharge stud welding processes overlap in some areas of application. Generally, the stud arc welding process is used in applications that require similar stud and workpiece metals, where the workpiece thickness is greater in relation to the stud diameter, and where an accommodation must be made for the stud flash (fillet). The term *flash* is preferred to the term *fillet*, because the metal that forms the flash during the stud arc welding process is expelled, rather than added, as occurs with other welding processes.

In contrast, the capacitor discharge stud welding process is used extensively when welding to thin sheet metal and is used frequently with dissimilar workpiece and stud alloys. It is also used in cases where marks on the opposite side of the workpiece must be avoided or minimized. With this process, the stud diameter is limited to smaller sizes. The capacitor discharge stud welding process is more fully described in the section "Capacitor Discharge Stud Welding" in this chapter. The factors on which process selection should be based are fastener size, base metal thickness, base metal composition, and reverse-side marking requirements.

A stud arc welding control system that has been integrated in a transformer/rectifier power source is shown in Fig. 4.3. This type of equipment, which is the most widely used, is called a power/control system. It can weld studs with diameters up to 28.5 mm (1.1 in.). Either a single gun or dual guns can be used. Although a light-duty control system can weigh 11.3 kg (25 lb), the system shown in Fig. 4.3 weighs approximately 450 kg (1000 lb) and can be put on a wheeled cart for mobility.

The stud arc welding process uses the same principles as any other arc welding procedure. First, the stud, which acts as an electrode, is inserted into a chuck on the end of the gun, surrounded by a ceramic ferrule, and positioned against the workpiece (Fig. 4.4a). Next, the gun trigger is depressed, which starts the automatic weld cycle by energizing a solenoid coil within the gun body that lifts the stud off the work and draws an arc. The arc melts the end of the stud and a portion of the workpiece (Fig. 4.4b). After a preset arc time (set on the control unit), the welding current is shut off and the solenoid is deenergized (Fig. 4.4c). A mainspring in the gun forces the stud into the molten pool of metal, producing a full-strength weld (Fig. 4.4d). The result is a full-penetration, full-strength stud-to-workpiece weld (Fig. 4.5). This weld is similar to that obtained with other types of arc welding processes.

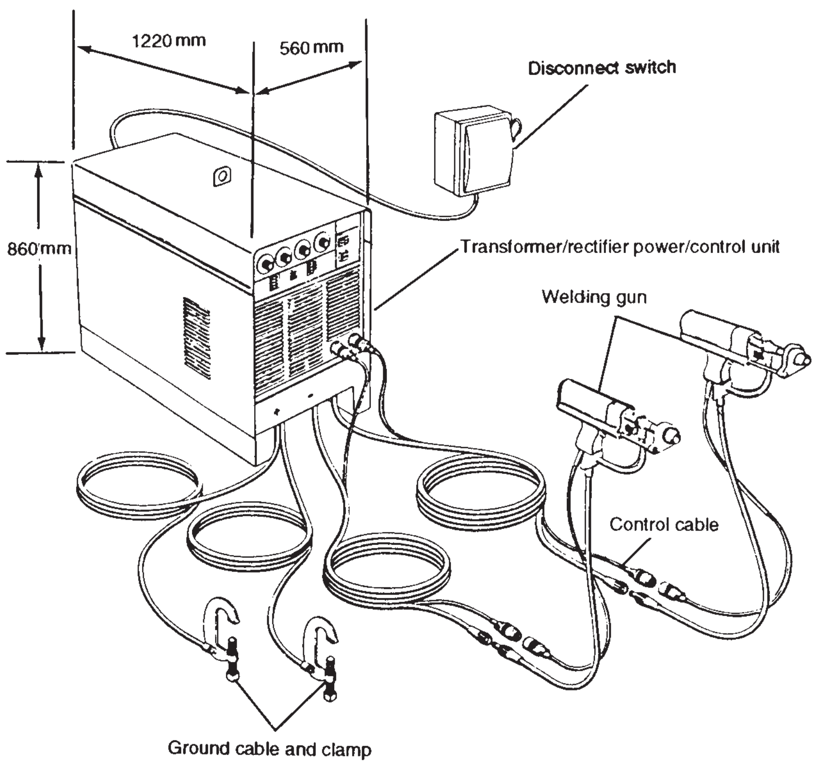

Fig. 4.3 Typical integrated power/control system for stud arc welding. Source: Ref 4.3

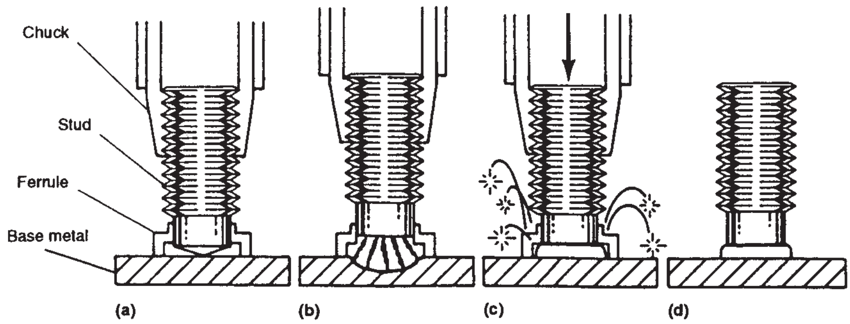

Fig. 4.4 Stud arc welding process: (a) gun is properly positioned; (b) trigger is depressed and stud is lifted, creating an arc; (c) arcing period is completed and stud is plunged into molten pool of metal on base material; (d) gun is withdrawn from welded stud and ferrule is removed. Source: Ref 4.3

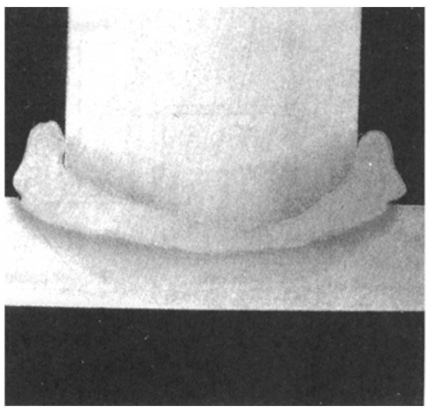

Fig. 4.5 Macrosection of low-carbon steel stud weld. Source: Ref 4.3

A wide range of studs are made by stud welding manufacturers for the stud arc welding process. They vary in size and weld base configuration, depending on the application requirements. Typical stud styles available are threaded, unthreaded, headed, and rectangular studs (Fig. 4.6). Steel stud diameters commonly welded using the stud arc welding process range from 2.7 to 25.4 mm (0.105 to 1.00 in.).

4.4 Capacitor Discharge Stud Welding

Capacitor discharge stud welding is a stud welding process in which the tip of the stud melts almost instantly when energy stored in capacitors is discharged through it. The three basic modes of capacitor discharge stud welding are initial-gap welding, initial-contact welding, and drawn-arc welding. Current-versus-time curves for the three modes are shown in Fig. 4.7.

Fig. 4.6 Common stud configurations for stud arc welding. Source: Ref 4.3

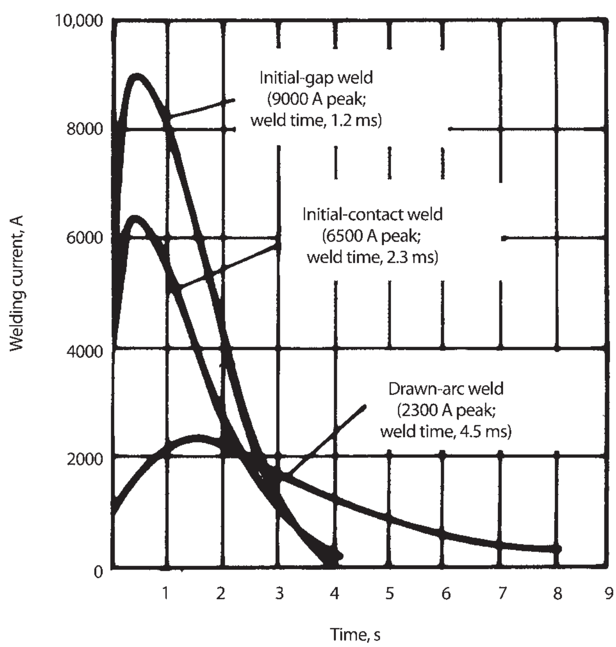

Fig. 4.7 Typical current-versus-time curves for the three capacitor discharge stud welding methods. Source: Ref 4.4

The initial-gap mode (Fig. 4.8a) is begun with the stud held away from the work surface by the welding head. At the beginning of the weld cycle, the stud is forced against the work surface, melting the tip, the face of the stud, and the adjoining work surface upon contact with the work surface. The weld is completed using the gun forces (i.e., spring pressure or air pressure) to plunge the stud into the molten materials, forming a strong welded bond between the stud and the work surface. The weld cycle time (Fig. 4.7) for this process is from 4 to 6 ms, and the penetration of the weld zone into the work surface is normally from 0.10 to 0.15 mm (0.004 to 0.006 in.).

The initial-contact mode (Fig. 4.8b) begins with the weld stud in contact with the work surface. The weld cycle is initiated with a surge of current that disintegrates the weld tip, melting the stud face area and the work surface that it immediately contacts. The stud is forced into the molten material, forming a strong homogeneous weld. This process has a weld cycle time of approximately 6 ms, much like the initial-gap process.

The drawn-arc mode (Fig. 4.8c) begins with the stud in contact with the work surface. When the weld cycle is initiated, a current surge is applied to the weld tip and the stud is retracted from the work surface, drawing an arc that melts the face of the stud and the work surface directly beneath it. The stud is then plunged into the molten pool of material, forming a welded connection. The weld cycle time for this process is longer than for the other two processes, and the heat-affected zone is thicker than it is in the preceding two processes.

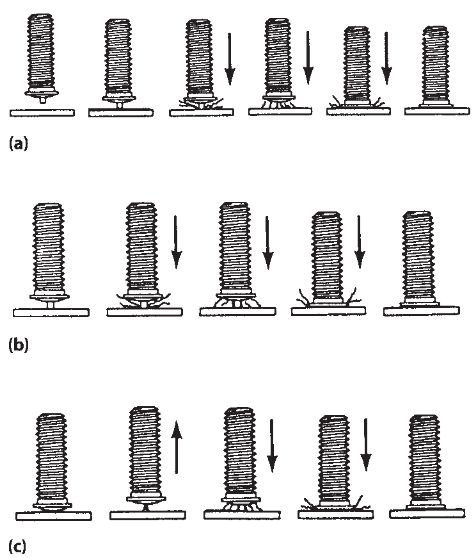

Fig. 4.8 Methods used for capacitor discharge (CD) stud welding, (a) initial-gap; (b) initial-contact; (c) drawn-arc. Source: Ref 4.4

A major reason for using the capacitor discharge stud welding process is that it provides a strong welded fastener with either a minimum or no reverse-side marking of the workpiece. Another reason is that it is cost-effective, especially for small-diameter fasteners. This process also allows fasteners to be welded to very thin sections, as well as to thick sections (as thick as necessary), with reliable results. Furthermore, the process allows the welding of many dissimilar material combinations, such as aluminum studs to zinc die castings. The disadvantages of using the capacitor discharge process are the limited stud diameters available and the fact that the work surface must be clean of mill scale, dirt, oxidation products, and oil.

The stud and workpiece materials can be common low-carbon steel, stainless steel, or aluminum. Also used are medium-carbon steel, lead-free brass and copper, Inconel, titanium, René 41, zirconium, gold, silver, and platinum.

4.5 High-Frequency Welding

High-frequency welding includes a number of processes in which metal-to-metal bonding is accomplished by using heat caused by the flow of high-frequency current at the faying surfaces, with upsetting forces perpendicular to the interface. Although similar in many respects, two separate high-frequency welding processes can be identified: high-frequency resistance welding and high-frequency induction welding, In high-frequency resistance welding, heating current enters the work through electrical contacts on the surface. In high-frequency induction welding, heating current is induced in the work through an external induction coil, and no physical or electrical contact between the workpiece and the power supply is needed (Fig. 4.9).

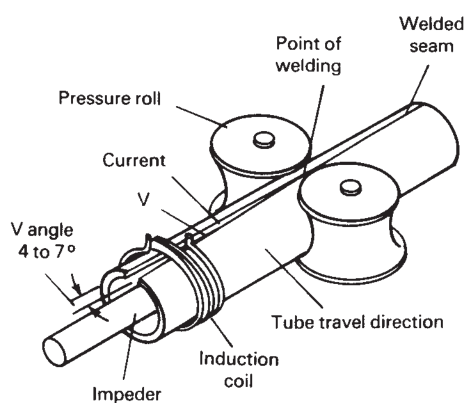

Fig. 4.9 Joining a tube seam by high-frequency induction welding. Source: Ref 4.5

In more conventional resistance welding processes, heating is accomplished at the joint interface by the flow of current across the interface as it passes between two electrodes pressed against the work. The current is normally direct current (dc) or low-frequency alternating current (ac), from 60 to 360 Hz. In some cases, the current may be the result of a capacitor discharge. Very high currents are required to heat the metal; large, well-cooled electrical contacts must be placed as close as possible to the desired weld, and high contact pressures are normally required.

In high-frequency welding, current flows in work surfaces parallel to the joint. The location of the current flow in the work surfaces is determined, for high-frequency resistance welding, by the location of the electrical contacts and external electrical conductors, and for high-frequency induction welding, by the design and location of the induction coil. The shape and relative position of the workpiece surfaces as they are brought together immediately before welding have a major influence in determining the current flow and concentration in continuous seam welding by both processes.

In high-frequency induction welding, the depth to which current flows depends on the frequency and the resistive and magnetic properties of the workpiece. At higher frequencies, current flow is shallower and more concentrated near the work surface. The range of frequencies used most often in this process is from 300 to 450 kHz, although frequencies as low as 10 kHz may be used in some instances. This concentration of current at the surface permits welding temperatures to be achieved with power consumption at much lower levels than with conventional resistance welding. The efficiency of welding is greatly increased, and relatively small contacts may be used.

Several factors must be considered in making successful high-frequency welds. Because of the advantages of concentrated heating, the process is inherently fast. Excessive conduction of heat away from the faying surfaces can diminish weld quality; thus, seam welding is performed at relatively high throughput speeds.

The advantages of high-frequency welding are that it is well suited for high-speed welding and can weld a large range of product sizes and materials. Weld quality is not particularly sensitive to the presence of air, and special atmospheres are usually not needed. Weld quality is relatively (but not completely) tolerant of surface oxides and contamination.

The disadvantages of high-frequency welding are that it is not well suited for low travel speeds and small-scale operations where welding is done by hand. High-frequency welding must be done continuously; continuous welds cannot be made in stop/start operations because a discontinuity in the weld will usually occur.

High-frequency welding is most suitable in applications that involve the continuous edge, or butt, joining of metals. The largest single use of high-frequency welding is in the manufacture of tube and pipe. Materials that can be successfully high-frequency welded into tube and pipe include carbon steels, stainless steels, aluminum, copper, brass, and titanium.

4.6 Electron Beam Welding

Electron beam welding is a high-energy-density fusion process that is accomplished by bombarding the joint to be welded with an intense and strongly focused beam of electrons that have been accelerated up to velocities 0.3 to 0.7 times the speed of light at 25 to 200 kV, respectively. The instantaneous conversion of the kinetic energy of these electrons into thermal energy as they impact and penetrate into the workpiece on which they are impinging causes the weld-seam interface surfaces to melt and produces the weld-joint coalescence. Electron beam welding is used to weld any metal that can be arc welded. The weld quality in most metals is equal to or superior to that produced by gas tungsten arc welding (GTAW).

Because the total kinetic energy of the electrons can be concentrated onto a small area on the workpiece, power densities as high as 10^8 W/cm^2 (10^7 W/in.^{2}) can be achieved. That is higher than is possible with any other known continuous beam, including laser beams. The high power density plus the extremely small intrinsic penetration of electrons in a solid workpiece result in almost instantaneous local melting and vaporization of the workpiece material. That characteristic distinguishes electron beam welding from other welding methods in which the rate of melting is limited by thermal conduction.

Basically, the electron beam is formed (under high-vacuum conditions) by employing a triode-style electron gun (Fig. 4.10) consisting of a cathode, a heated source (emitter) of electrons that is maintained at some high negative potential; a specially shaped electrode that can be negatively biased with respect to the hot cathode emitter (filament); and an anode, a ground potential electrode through which the electron flow passes in the form of a collimated beam.

One of the prime advantages of electron beam welding is the ability to make welds that are deeper and narrower than arc welds, with a total heat input that is much lower than that required in arc welding. This ability to achieve a high weld depth-to-width ratio eliminates the need for multipass welds, as is required in conventional arc welding. The lower heat input results in a narrow workpiece heat-affected zone and noticeably less thermal effects on the workpiece.

4.7 Laser Beam Welding

Laser beam welding is a joining process that produces coalescence of materials with the heat obtained from the application of a concentrated coherent light beam impinging on the surfaces to be welded. The word

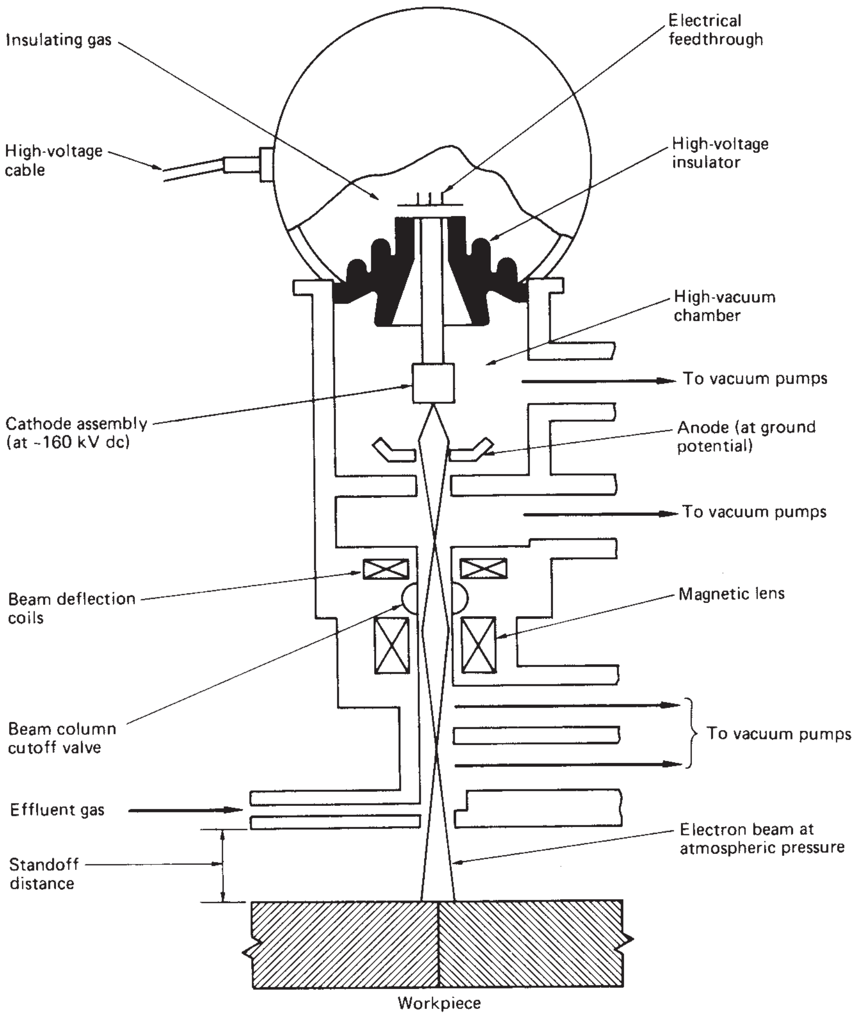

Fig. 4.10 Primary components of an electron beam welding unit. Source: Ref 4.6

laser is an acronym for "light amplification by stimulated emission of radiation." The laser can be considered, for metal joining applications, as a unique source of thermal energy, precisely controllable in intensity and position. For welding, the laser beam must be focused to a small spot size to produce a high power density. This controlled power density melts the metal and, in the case of deep-penetration welds, vaporizes some of it. When solidification occurs, a fusion zone or weld joint results. The laser beam, which consists of a stream of photons, can be focused and directed by optical elements (mirrors or lenses), as illustrated in the typical setup shown in Fig. 4.11. The laser beam can be transmitted through the air for appreciable distances without serious power attenuation or degradation.

The two kinds of industrial laser welding processes, conduction limited (or melt-in) and deep penetration (or keyhole), are illustrated in Fig. 4.12. Both processes are normally autogenous; they use only the parent metal with no added filler. In conduction-limited laser beam welding, the metal absorbs the laser beam at the work surface. The subsurface region is

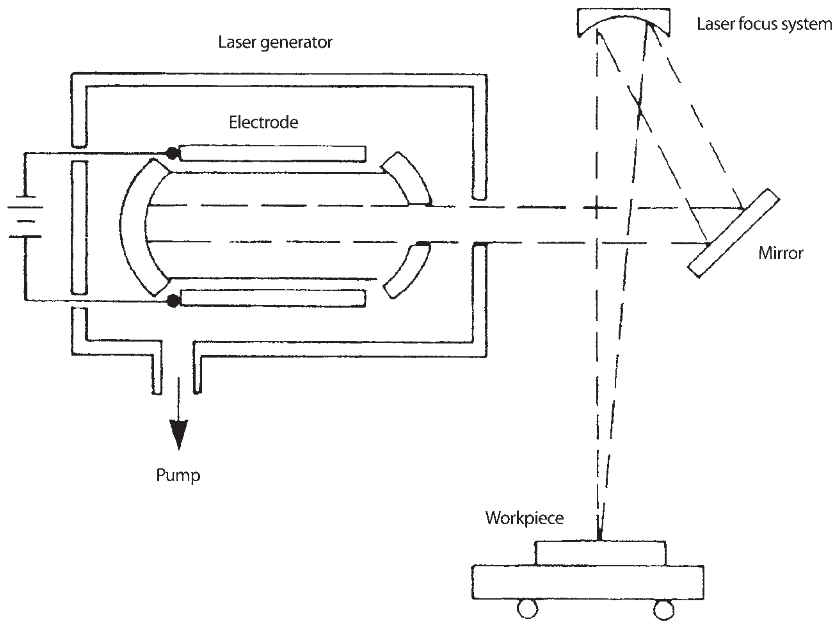

Fig. 4.11 Primary components of a laser beam welding unit. Source: Ref 4.7

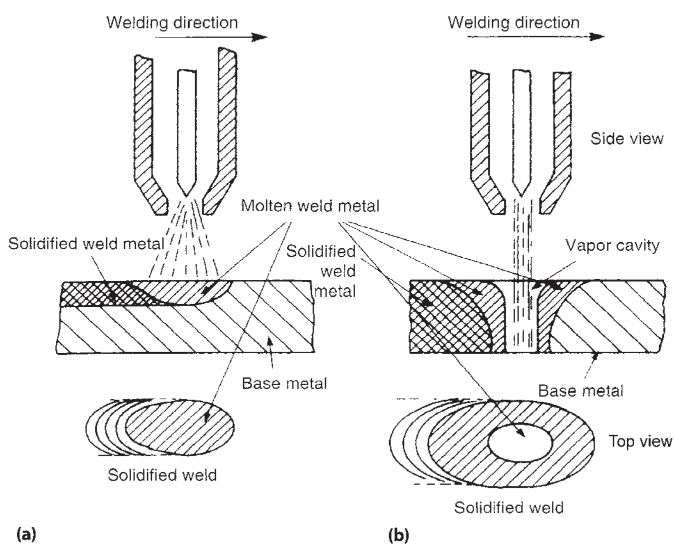

Fig. 4.12 Comparison of (a) melt-in or conduction versus (b) keyhole welding mode. Source: Ref 4.7

heated entirely by thermal conduction. Conduction-limited laser beam welding uses solid-state and moderate-power carbon dioxide (CO_2) lasers and is normally performed with low average power (≤1 kW). Deep-penetration laser beam welding requires a high-power CO_2 laser. Thermal conduction does not limit penetration; laser beam energy is delivered to the metal through the depth of the weld, not just to the top surface. Deep-penetration laser beam welding is similar to high-power electron-beam welding in a vacuum. A photomicrograph of a deep-penetration weld is shown in Fig. 4.13.

The automotive, consumer products, aerospace, and electronics industries all use laser beam welding to join a variety of materials. Among the

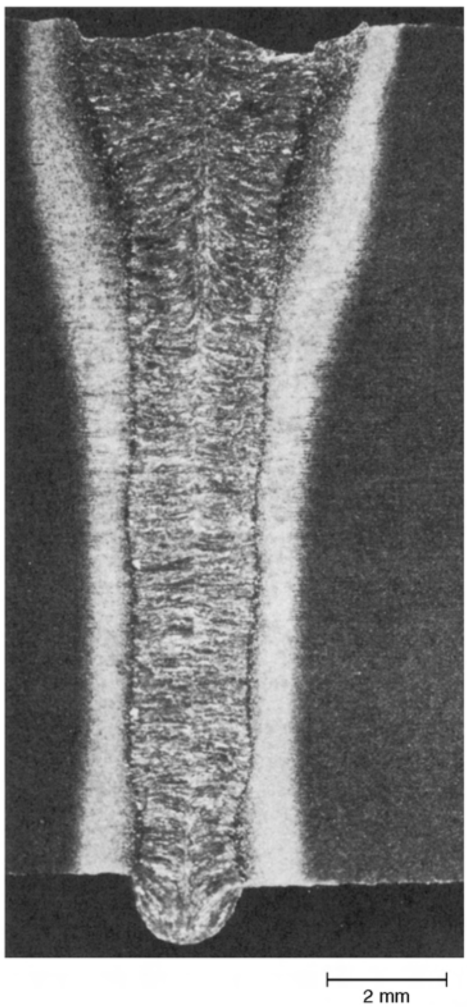

Fig. 4.13 Single-pass deep-penetration autogenous laser butt weld in 14 mm (9/16 in.) A-710 steel plate. Macrograph shows the high depth-to-width ratio of the weld bead and the limited size of the heat-affected zone. Source: Ref 4.8

weldable metals are lead, precious metals and alloys, copper and copper alloys, aluminum and aluminum alloys, titanium and titanium alloys, refractory metals, hot and cold-rolled carbon and low-alloy steels, high-strength low-alloy (HSLA) steels, stainless steels, and heat-resistant nickel and iron-base alloys. Porosity-free welds can be attained with tensile strengths equal to or exceeding those of the base metal.

4.8 Hybrid Laser Arc Welding

Hybrid laser arc welding (HLAW), also known as laser-hybrid welding or simply hybrid welding, is a metal joining process that combines laser beam welding and arc welding in the same weld pool. Gas tungsten arc welding (GTAW), gas metal arc welding (GMAW), and plasma arc welding have been used; however, GMAW has become the most popular arc process for HLAW. Historically, high-power continuous-wave lasers such as carbon dioxide (CO_2) gas lasers and solid-state neodymium-doped yttrium aluminum garnet (Nd:YAG) lasers have been used; however, with advancements in the performance of other solid-state technologies, fiber lasers, thin-disk lasers, and semiconductor diode lasers are increasingly used for HLAW.

The high energy density from the laser process can provide deep weld penetration and high processing speeds. The process can provide lower heat input and less distortion than conventional arc welding. It can also produce narrow welds with small heat-affected zones. Filler material from the GMAW process can provide alloying additions and joint filling that is not possible with autogenous laser welding. Although HLAW is a productive and advantageous welding process, precise alignment and strict part fit-up are required to maintain weld consistency and quality. It is used only in mechanized or automated applications. Because of the expensive laser equipment, the capital cost for HLAW systems can be 10 to 50 times higher than conventional automated GMAW systems.

Hybrid laser arc welding can be divided into two groups based on the mechanism for which the laser is used. One is a stabilization mode, where the laser is used to augment the GMAW process without providing a significant increase in penetration or speed. The other is a penetration mode, where the laser generates a keyhole in the metal, providing both deep penetration and high processing speeds. The process can be oriented in two directions (Fig. 4.14): arc leading or laser leading. The GMAW process can be positioned behind or in front of the traveling laser keyhole. If the GMAW process travels behind the laser beam, the HLAW process orientation is referred to as *laser leading*. If the GMAW process travels ahead of the laser, the process orientation is referred to as *arc leading*.

The main difference between the two orientations is the angle of the GMAW torch with respect to the direction of travel. Torch angle can have an effect on the deposited GMAW bead. In the laser-leading configura-

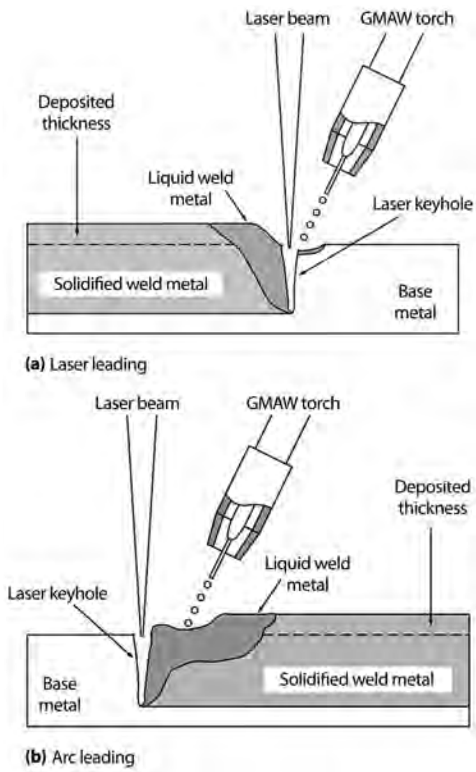

Fig. 4.14 Hybrid laser arc welding variations. Source: Ref 4.9

tion, the GMAW torch is traveling behind the laser beam, positioned at a "push angle." In the arc-leading configuration, the torch is at a "drag angle," traveling in front of the laser beam. This difference in torch angle can produce different weld surface geometries. In the laser-leading orientation, the deposited weld bead is relatively wide and flat, with large weld toe angles. With arc leading, the deposited weld bead is narrower and more convex, with sharper weld toe angles. Torch angle can be adjusted for each process orientation, but there is a limitation to how close the torch can be positioned to the beam axis due to the beam convergence angle and obstructions from the laser focusing optic assembly. Alternatively, the laser beam axis can be tilted while the GMAW torch is positioned normal to the work.

Hybrid laser arc welding can be used to weld a wide range of metals, including steel, stainless steel, nickel, titanium, aluminum, copper, and other alloy systems. With the high productivity and the broad range of alloys that can be welded, many industries currently using GMAW or submerged arc welding could benefit from hybrid welding. The process is suitable for applications where a productivity increase can justify the high capital cost of an automated hybrid welding system. These can be high-volume production applications or low-volume applications that require an extensive amount of welding. The HLAW process can increase productivity by providing faster processing speeds or deeper penetration.

4.9 Thermit Welding

Thermit welding is a process that produces coalescence of metals by heating them with superheated liquid metal from an aluminothermic reaction between a metal oxide and aluminum, with or without the application of pressure. Filler metal is obtained from the liquid metal. The aluminothermic reaction associated with the thermit process produces pure carbon-free heavy metals, such as chromium, manganese, or vanadium from ores, oxides, or chlorides. Introduction of this process constituted a major technological breakthrough, because when these metals are generated by the electrothermic processes, they have high carbon contents that are unacceptable for many metallurgical applications.

The aluminothermic reaction that uses aluminum as a reductant takes place according to the general equation:

$$\text{Metal oxide} + \text{aluminum} \rightarrow \text{metal} + \text{aluminum oxide} + \text{heat}$$

or, more specifically:

$$Fe_2O_3 + 2Al \rightarrow 2Fe + Al_2O_3 + \text{Heat} \uparrow (850 \text{ kJ})$$

The intense superheat set free during the reaction generates iron and aluminum oxide in liquid form. Because each component has a different density, they separate automatically within seconds, and the liquid iron can be used for different welding applications or for the production of metals and alloys. The theoretical temperature achieved by reducing iron oxide with aluminum is about 3100 °C (5600 °F).

The most common application of the process is the welding of rail sections into continuous lengths (Fig. 4.15). It is an effective way to minimize the number of bolted joints in the track structure. The thermit welding of rails, including a short preheat, involves these basic operations:

1. Cut or space the rails to be welded so that the gap specified by the manufacturer is achieved
2. Remove slag, moisture, foreign matter, and such from the area to be welded.
3. Align the rail ends, both vertically and horizontally.
4. Center the thermit molds over the rail gap and seal the gaps with luting material.
5. Situate the preheating equipment, mold clamps, and thermit crucible in position above the joint gap and the mold opening.
6. Adjust the preheating equipment to achieve the most uniform heating of the rail ends from one side to the other and from top to bottom.

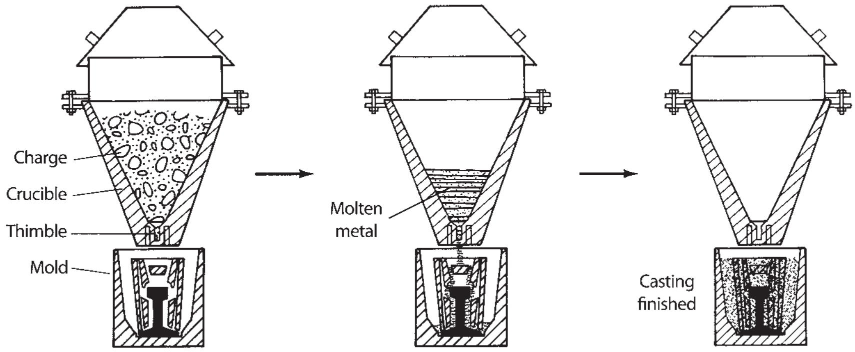

Fig. 4.15 Typical crucible-mold setup for rail thermit welding. Source: Ref 4.10

7. Ignite the thermit charge and allow it to tap into the mold, the timing of which is usually controlled by a self-tapping thimble. The liquid metal flows onto a diverter plug to redirect the flow of liquid metal into the side sprues so that the casting is produced from the bottom upward
8. Allow the proper solidification time.
9. Remove the mold material and finish-grind the weld to railroad specifications.
10. Conduct a final inspection of the weld, both visually and with the aid of ultrasonic equipment.

The thermit welding process also is used to weld electrical conducting joints, particularly to provide electrical continuity for railroad signal systems. A copper oxide powder is reduced by aluminum to form a metallurgical bond between the steel rail and the copper conductor. The resulting joint has excellent current-carrying capacity. Large-diameter rolls, shafts, ingot molds, and heavy mill housings can be successfully repaired by using the thermit welding process.

ACKNOWLEDGMENTS

Sections of this chapter were adapted from "Other Fusion Welding Processes" in *Metals Handbook Desk Edition,* 2nd ed., ASM International, 1998; and from "Hybrid Laser-Arc Welding" by B.M. Victor in *Welding Fundamentals and Processes,* Vol 6A, ASM International, 2011.

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CHAPTER 5

Metallurgy Variables in Fusion Welding

FUSION WELDING is the joining of two or more pieces of material by melting a portion of each and allowing the liquefied portions to solidify together. One distinguishing feature of all fusion welding processes is the intensity of the heat source used to melt the liquid. Virtually every concentrated heat source has been used for fusion welding. However, many of the characteristics of each type of heat source are determined by its intensity. For example, when considering a planar heat source diffusing into a very thick slab, the surface temperature will be a function of both the surface power density and the time. Figure 5.1 shows how this temperature will vary on steel with power densities that range from 400 to 8000 W/cm^2. At the lower value, it takes 2 min to melt the surface. If that heat source were

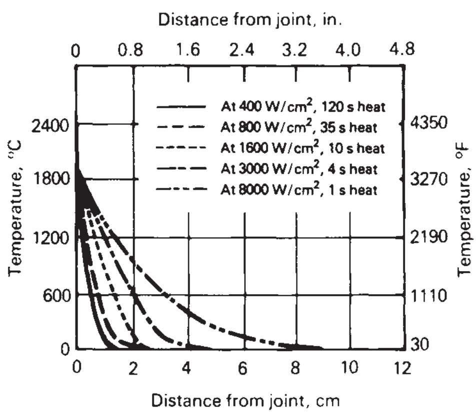


Fig. 5.1 Temperature distribution after a specific heating time in a thick steel plate heated uniformly on one surface as a function of applied heat intensity; initial temperature of plate is 25 °C (77 °F). Source: Ref 5.1

a point on the flat surface, then the heat flow would be divergent and might not melt the steel. Rather, the solid metal would be able to conduct away the heat as fast as it was being introduced. It is generally found that heat-source power densities of approximately 1000 W/cm^2 are necessary to melt most metals. At the other end of the power-density spectrum, heat intensities of 10^6 or 10^7 W/cm^2 will vaporize most metals within a few microseconds. At levels above these values, all of the solid that interacts with the heat source will be vaporized, and no fusion welding can occur. Thus, the heat sources for all fusion welding processes should have power densities between approximately 0.001 and 1 MW/cm^2.

Materials with higher thermal diffusivities—or the use of a local point heat source rather than a planar heat source—will increase the time to produce melting by a factor of up to two to five times. On the other hand, thin materials tend to heat more quickly. Heat sources with power densities that are of the order of 1000 W/cm^2, such as oxyacetylene flames or electroslag welding, require interaction times of 25 s with steel, whereas laser and electron beams, at 1 MW/cm^2, need interaction times on the order of only 25 μs.

Welders often begin their training with the oxyacetylene process. It is inherently slow and does not require rapid response time in order to control the size of the weld puddle. Greater skill is needed to control the more rapid fluctuations in arc processes. The weld pool created by the high-heat-intensity processes, such as laser beam and electron beam welding, cannot be humanly controlled and must therefore be automated. This need to automate leads to increased capital costs. On an approximate basis, the power densities (W/cm^2) of a process can be substituted with the dollar cost of the capital equipment. With reference to Fig. 5.2, the cost of oxyacetylene welding equipment is nearly $1000, whereas a fully automated laser beam or electron beam system can cost more than $1 million. Note that the capital cost includes only the energy source, control system, fixturing, and materials handling equipment. It does not include operating maintenance or inspection costs, which can vary widely depending on the specific application.

At high heat intensities, nearly all of the heat is used to melt the material and little is wasted in preheating the surroundings. As the heat inten-

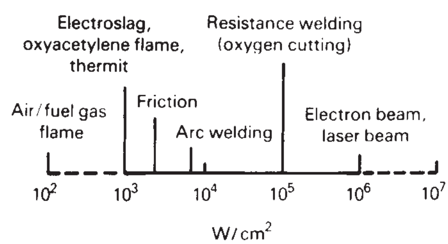


Fig. 5.2 Spectrum of practical heat intensities used for fusion welding. Source: Ref 5.1

sity decreases, this efficiency is reduced. For arc welding, as little as half of the heat generated may enter the plate, and only 40% of this heat is used to fuse the metal. For oxyacetylene welding, the heat entering the metal may be ≤10% of the total heat, and the heat necessary to fuse the metal may be <2% of the total heat. The heat intensity also controls the depth-to-width ratio of the molten pool. This ratio can vary from 0.1 in low-heat-intensity processes to >10 in high-heat-intensity processes.

5.1 Heat Flow

During fusion welding, the thermal cycles produced by the moving heat source causes physical state changes, metallurgical phase transformations, and transient thermal stresses and metal movement. The intense welding heat melts the metal and forms a molten pool. Some of the heat is conducted into the base metal, and some is lost from either the arc column or the metal surface to the environment surrounding the plate. Three metallurgical zones are formed in the plate upon completion of the thermal cycle: the weld metal zone, the heated-affected zone (HAZ), and the base metal zone. The peak temperature and the subsequent cooling rates determine the HAZ structures, whereas the thermal gradients, the solidification rates, and the cooling rates at the liquid-solid pool boundary determine the solidification structure of the weld metal zone. The size and flow direction of the pool determine the amount of dilution and weld penetration. The material response in the temperature range near melting temperatures is primarily responsible for the metallurgical changes.

The effects of material thermal properties on isotemperature contours are shown in Fig. 5.3 for stainless steel, steel, and aluminum. The temperature spreads over a larger area and causes a larger weld pool (larger weld bead), and the isotemperature contours elongate more toward the back of the arc, for low-conductivity materials (Fig. 5.3a). For aluminum (Fig. 5.3c), a larger heat input would be required to obtain the same weld size as the stainless steel weldment. The effect of travel speed on isotemperature contours is illustrated in Fig. 5.4. When the travel speed increases, the weld size decreases and the isotemperature contours are more elongated toward the back of the arc. Larger heat inputs would be required for faster travel speeds in order to obtain the same weld size.

5.2 Weld Solidification

Weld metal solidification behavior controls the size and the shape of grains, the extent of segregation, the distribution of inclusions, the extent of defects such as porosity and hot cracking, and the properties of the weld metal.

Inherent to the welding process is the formation of a molten weld pool directly beneath the heat source which contains impurities. The molten

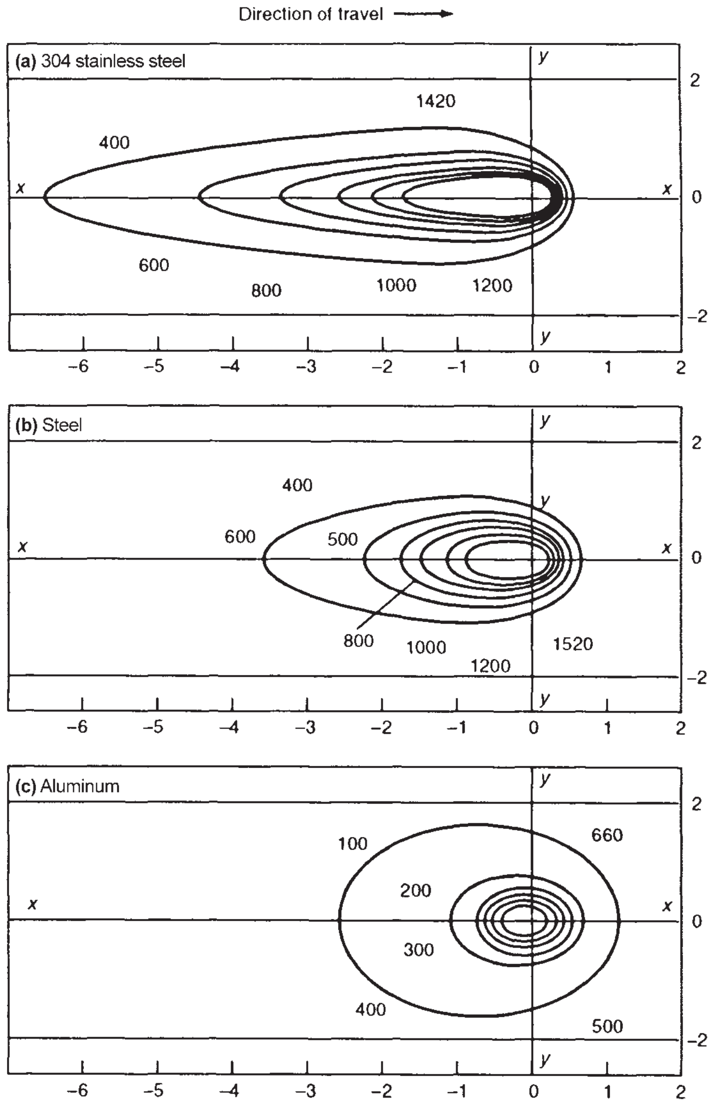


Fig. 5.3 Effect of thermal properties on isotemperature contours (in °C) for a heat input of 4.2 kJ/s (1000 cal/s) at a travel speed of 5 mm/s (0.02 in./s) and the thermal conductivities of each material. Values on x- and y-axes are in centimeters and temperatures are in centigrade. Source: Ref 5.2

metal volume is small compared with the size of the base metal. The composition of the molten metal is similar to that of the base metal. There are large temperature gradients across the melt. The weld metal shape is influenced by both the resultant heat and fluid (or metal) flow. Significant turbulence (i.e., good mixing) takes place in the molten pool. The heat input determines the volume of the molten metal, and therefore dilution, weld metal composition, and thermal condition. Because the heat source moves, weld solidification is a dynamic process comprising very rapid localized

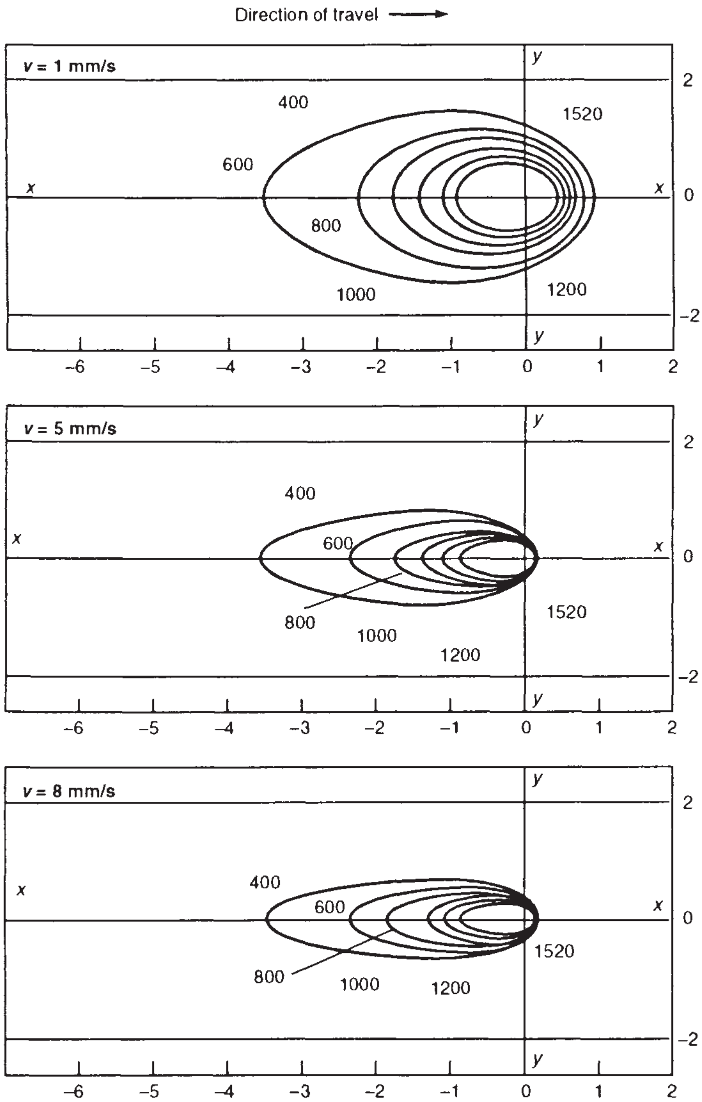


Fig. 5.4 Effect of travel speed on isotemperature contours of low-carbon steel for 4.2 kJ/s (1000 cal/s) heat input. Source: Ref 5.2

melting and freezing. A weld can be thought of as a miniature casting. However, a very large temperature gradient develops in a weld. The center of a weld pool reaches a very high temperature (typically 2000 to 2500 °C, or 3630 to 4530 °F), which is limited by the vaporization of the weld metal. At the sides of the weld pool, where solidification is taking place, the temperature is the solidification temperature, which is typically about 1000 °C (1800 °F) less than the temperature at the center of the weld pool.

The development of weld pool geometry is influenced by the amount of heat transfer from the heat source to the workpiece, the travel speed, the nature of fluid flow in the weld pool, and the rate at which heat can be removed at the liquid-solid interface. At low heat inputs and slow travel speeds, an elliptical weld pool forms and columnar grains form along the welding direction (Fig. 5.5a). At high heat inputs and high travel speeds, the weld pool becomes teardrop shaped and the columnar grains are straighter (Fig. 5.5b). In both situations, grain growth begins from the substrate at the fusion boundary and advances toward the weld center. An elliptical or spherical pool is usually observed in weldments of metals with a higher diffusivity (e.g., aluminum), whereas a teardrop-shaped weld pool is more likely in the weldments of metals with a low thermal diffusivity (e.g., austenitic stainless steels). In most commercial aluminum alloys, low-carbon steels, and 304 stainless steels at a higher travel speed (730 to 40 cm/s, or 1.2 to 1.6 in./s), equiaxed grains are found near the weld centerline (Fig. 5.5c). In this case, the competitive growth changes

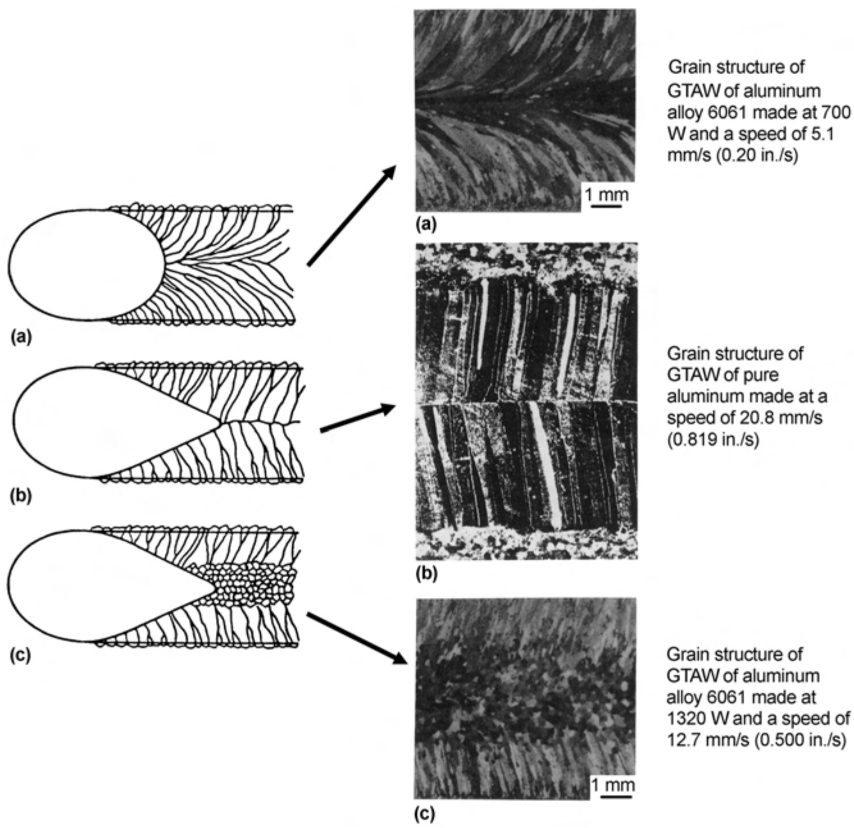


Fig. 5.5 Schematic showing effect of heat input and welding speed variations on weld grain structure in gas tungsten arc welding (GTAW): (a) low heat input and low welding speed, producing an elliptical weld pool; (b) high heat input and high welding speed, producing a tear-drop shaped weld pool- Here, the heat input and welding speed are not yet sufficient to cause heterogeneous nucleation at the weld pool centerline; and (c) high heat input and high welding speed with heterogeneous nucleation at the weld pool centerline. Source: Ref 5.3

from columnar grains to the nucleation and growth of equiaxed grains in the bulk metal similar to that noticed in ingots and castings.

Depending on the cooling conditions, a number of solidification structures are possible (Fig. 5.6a to e). For curve *a* (Fig. 5.6f), the temperature gradient is steeper than the liquidus curve, and only planar solidification is

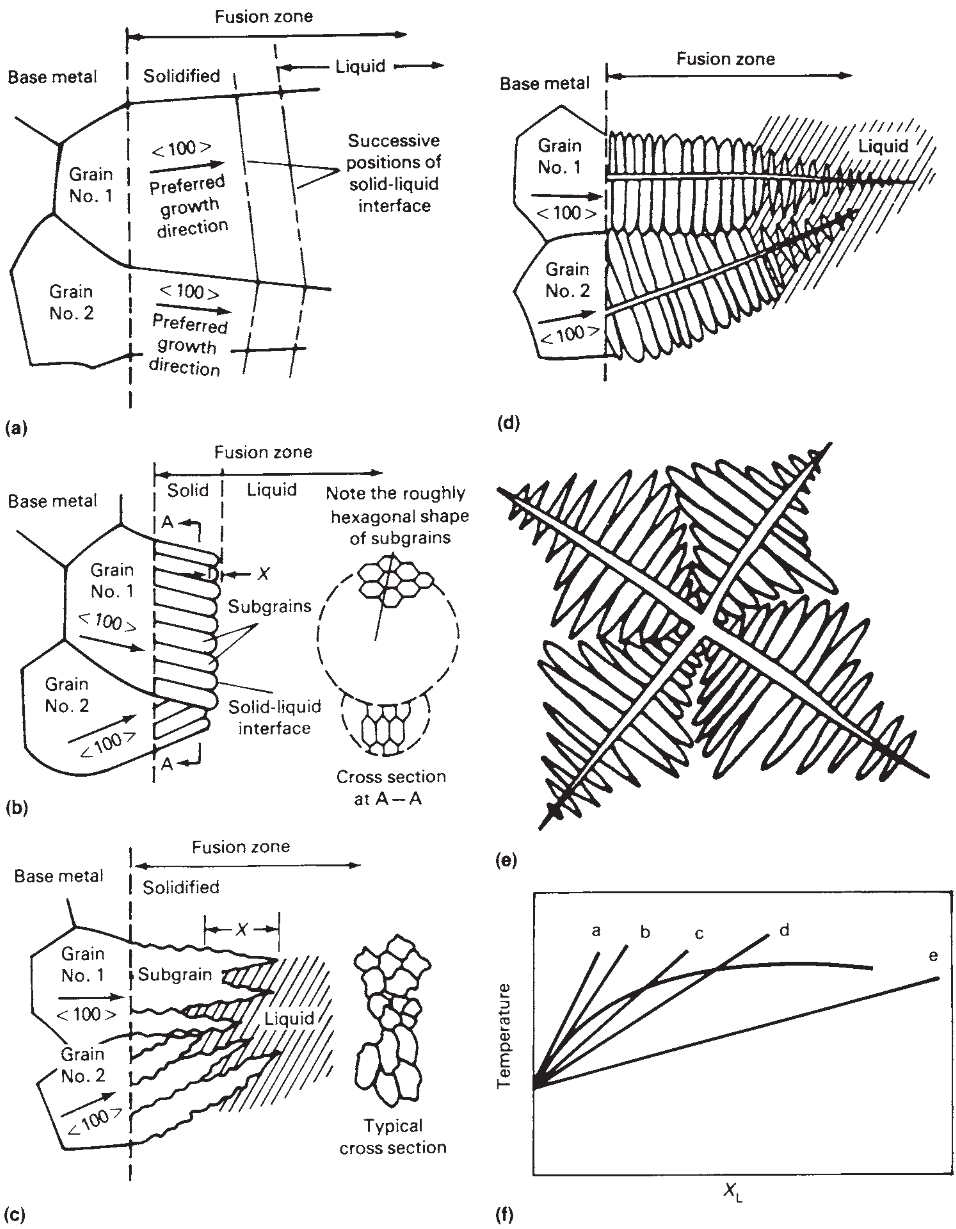


Fig. 5.6 Schematics showing microstructure of solid-liquid interface for different modes of solidification and the temperature gradients that generate each mode; <100> is the preferred crystallographic growth direction. X_L is the distance into the liquid that is ahead of the solid-liquid interface: (a) planar growth, (b) cellular growth, (c) cellular dendritic growth, (d) columnar dendritic growth, (e) equiaxed dendritic, and (f) five temperature gradients versus constitutional supercooling. Source: Ref 5.3

possible. For curve *b*, there is a shallower gradient and the solid-liquid interface can move by cellular growth. The gradient is successively lower for *c* and *d*, which allows larger protrusions and the development of cellular dendritic and columnar dendritic growth. At curve *e*, the gradient is so shallow and the resulting liquidus is so far above the actual temperature in the liquid that equiaxed dendrites can form ahead of the solid-liquid interface.

A metallographic cross section of a solidified welded joint will exhibit three distinct zones: the fusion zone, also called the weld metal, the unmelted but heat-affected zone (HAZ), and the unaffected base metal (Fig. 5.7a). The characteristics of the fusion zone depend, to a great extent, on the solidification behavior of the weld pool. However, on closer metallographic examination, the fusion zone can be further divided into the composite zone, the unmixed zone, and the partially melted zone (Fig. 5.7c). The unmixed zone occurs in welds with filler metal additions and consists of molten base metal and a resolidified zone without mixing with filler metal additions during the movement of the weld pool.

5.3 Solid-State Transformations

Depending on the composition of the metal or alloy and the manner in which it has been strengthened, the heat of welding will alter its strength and ductility in the HAZ. The main classes of metals and alloys include work- or strain-hardened metals and alloys, precipitation-hardened alloys, transformation-hardened steels and cast irons, sensitization of stainless steels, and solid-solution and dispersion-hardened alloys.

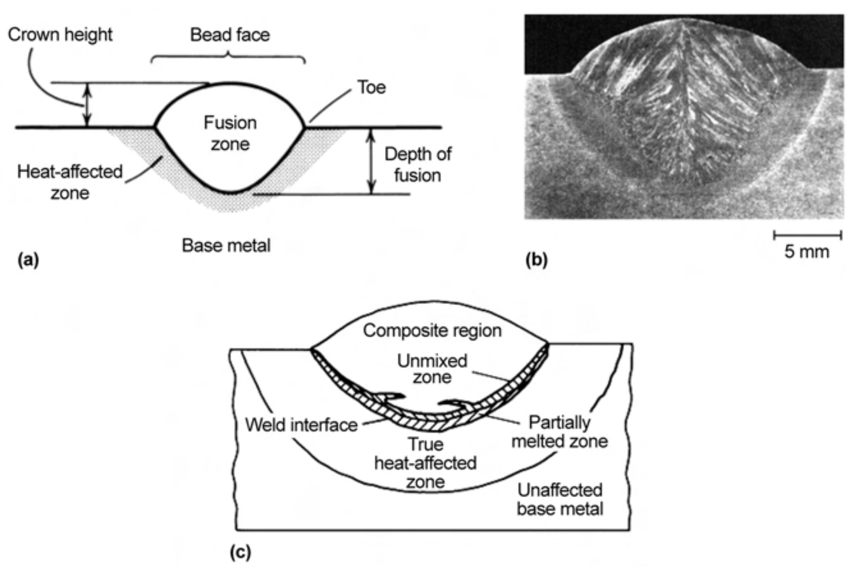


Fig. 5.7 The different discrete regions present in a single-pass weld. Source: Ref 5.4, p 1047–1056; Ref 5.5

5.3.1 Work- or Strain-Hardened Metals and Alloys

When a pure metal or an alloy is subjected to severe mechanical working at room temperature, it becomes stronger along with a ductility decrease in a process known as work or strain hardening. When the work-hardened metal or alloy is subjected to temperatures more than approximately 0.4–0.5 T_m (absolute melting temperature), the deformed grains dissolve and nucleate new strain-free grains in a process known as recrystallization. With increasing temperature, the metal or alloy goes through three progressive steps: recovery, recrystallization, and grain growth. Residual stresses are relieved during recovery, but strength and ductility are largely retained. At higher temperatures, recrystallization occurs through the formation of new strain-free grains, and the strength decreases while the ductility increases. Finally, at even higher temperatures, grain growth occurs that does not affect the static strength but can be detrimental to the ductility and fatigue strength. These property effects at the HAZ, and a schematic representation of the microstructural effects, are shown in Fig. 5.8. These property effects can be minimized by limiting the heat of welding through the selection of a high-energy-density process or by using a very fast heating process. After welding, mechanical peening, stretching, or roller planishing can be used to restore some of the original properties.

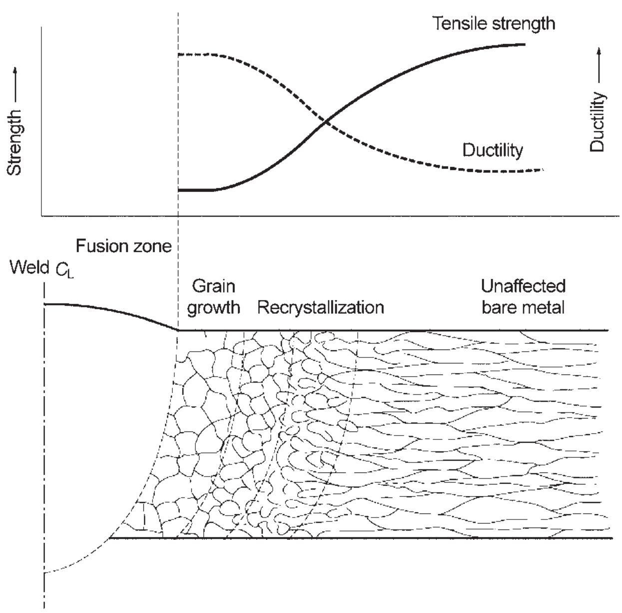


Fig. 5.8 Effects of the heat of welding, brazing, or soldering on the properties (top) and microstructure (bottom) of a work-hardened metal. Source: Ref 5.6, p 476

5.3.2 Precipitation-Hardened Alloys

A number of high-strength structural alloys are strengthened by precipitation hardening processes. Notable among these alloy groups are heat-treatable aluminum alloys (2*xxx*, 6*xxx*, 7*xxx* and the lithium-containing 8*xxx* alloys), nickel-based alloys containing aluminum and/or titanium, precipitation-hardening stainless steels, and maraging steels. These alloys are hardened by heating to a relatively high temperature to create a supersaturated solid solution and then quenching to room temperature to retain the supersaturated solid solution. On aging at an intermediate temperature, a coherent second phase precipitates from the supersaturated solid solution. These coherent second-phase particles strain the matrix and block the motion of dislocations, thus strengthening the alloy. The high heat from welding causes two types of strength degradation:

- *Reversion* occurs in the HAZ near the fusion zone where the heat is sufficiently high that the precipitate particles dissolve back into solution.
- *Overaging* occurs farther from the fusion zone, but still in the HAZ, as the precipitate particles grow in size and lose coherency with the matrix.

These property effects are shown in Fig. 5.9. The strength loss can be minimized by minimizing the heat of welding through selection of a high-

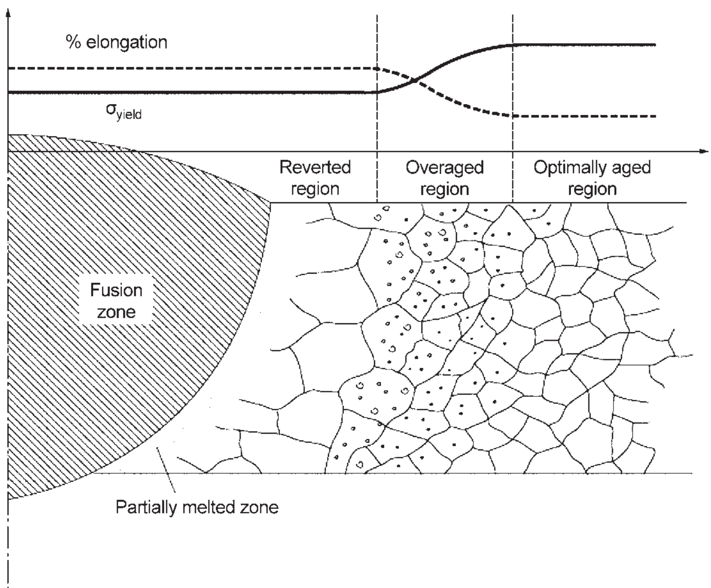


Fig. 5.9 Effect of the heat of welding, brazing, or soldering on the properties (top) and microstructure (bottom) of an age-hardened precipitation hardenable alloy. Source: Ref 5.6, p 478

energy-density process or a very fast heating process during welding. An additional method is to weld the alloy in the solution-treated condition and then age the finished weldment. This might be acceptable because the temperature for aging is considerably lower than the temperature for solutionizing, so it will tend to create less distortion.

5.3.3 Transformation-Strengthened Steels and Cast Irons

Steels that contain sufficient carbon to be hardened by martensitic formation on quenching and then tempering run the danger of developing untempered martensite during cooling. Since untempered martensite is extremely brittle and the lattice strains are high, immediate or delayed weld cracking can occur. Depending on the cooling rate, one of two outcomes is possible. If the cooling rate from welding is slow, ferritic type structures will form rather than martensite. Ferritic type structures, such as pearlite, are susceptible to weld cracking, but the strength will be lower than anticipated. However, if the cooling rate is rapid, then untempered martensite will form. In the case of a hardened steel that is welded, there will also be a zone containing material that is tempered past its peak properties. Potential solutions are to: (a) slow down the cooling rate to avoid the formation of untempered martensite or (b) use a postweld heat treatment to temper any untempered martensite.

5.3.4 Sensitization of Stainless Steels

Although stainless steels provide resistance against general corrosion and pitting, austenitic stainless steels can be susceptible to intergranular corrosion by sensitization. Susceptible stainless steels are those that have normal carbon contents (generally 70.04 wt%) and do not contain titanium and niobium carbide stabilizing elements. Sensitization is caused by the precipitation of chromium carbides at grain boundaries during exposure to temperatures from 450 to 870 °C (840 to 1600 °F), with the maximum effect occurring near 675 °C (1250 °F). The resulting depletion in chromium adjacent to the chromium-rich carbides provides a selective path for intergranular corrosion. Precipitation commonly occurs from the heat of welding.

An effective means of combating intergranular corrosion in stainless steels is to restrict the carbon content to the alloy. In the stainless L-grades, limiting the carbon content of a maximum of 0.03 wt% is often sufficient. High chromium and molybdenum additions also reduce the chance of intergranular attack. However, even better performance can be obtained from the stabilized types, which contain sufficient titanium and niobium that combine preferentially with carbon to form titanium and niobium carbides.

5.3.5 Solid-Solution and Dispersion-Strengthened Metals

The heat of welding really has no effect on pure metals, single-phase solid-solution-strengthened alloys, or dispersion-strengthened alloys. Solid-solution-strengthened alloys might experience some grain growth, which could lower ductility more than strength. However, this should not occur in dispersion-strengthened metals or alloys, since the dispersoid will limit grain growth. Figure 5.10 illustrates typical hardness traverses across welds made in metals and alloys strengthened by various means.

5.4 Residual Stresses and Distortion

Complex thermal stresses occur in parts during welding due to the localized application of heat. Residual stresses and distortion remain after welding is completed. Transient thermal stresses, residual stresses, and distortion sometimes cause cracking and mismatching of joints. High-tensile residual stresses in areas near the weld can cause premature failures of welded structures under certain conditions. Distortion, especially out-of-plane distortion, and compressive residual stresses in the base plate can reduce the buckling strength of a structural member subjected to com-

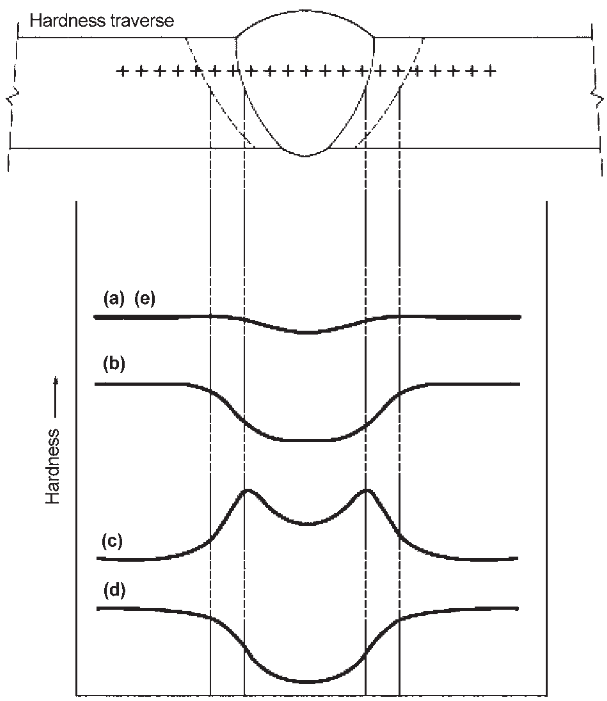


Fig. 5.10 Typical hardness traverses across a single-pass fusion weld made in metals or alloys strengthened by (a) solid-solution alloying, (b) precipitation hardening, (c) transformation hardening, (d) work hardening, and (e) dispersion strengthening. Source: Ref 5.6, p 482

pressive loading. Correction of unacceptable distortion is costly and, in some cases, impossible.

Residual stresses are stresses that exist in a body after all external loads are removed. Because a weldment is locally heated by the welding heat source, the temperature distribution is not uniform and changes as welding progresses. During the welding thermal cycle, complex transient thermal stresses are produced in the weldment and the surrounding joint. The weldment also undergoes shrinkage and deformation during solidification and cooling.

The changes in temperature and resulting stresses that occur during welding, by examining a bead-on-plate weld of a thin plate made along the *x*-axis, are shown in Fig. 5.11. The welding arc, which is moving at speed *v*, is presently located at the origin, *O* (Fig. 5.11a). The area where plastic deformation occurs during the welding thermal cycle is shown by the shaded area, *M–M′*. The region where the metal is molten is indicated by the ellipse near *O*. The region outside the shaded area remains elastic throughout the entire welding thermal cycle.

Temperature gradients along several cross sections through the weld bead path are indicated in Fig. 5.11(b). In the base metal ahead of the

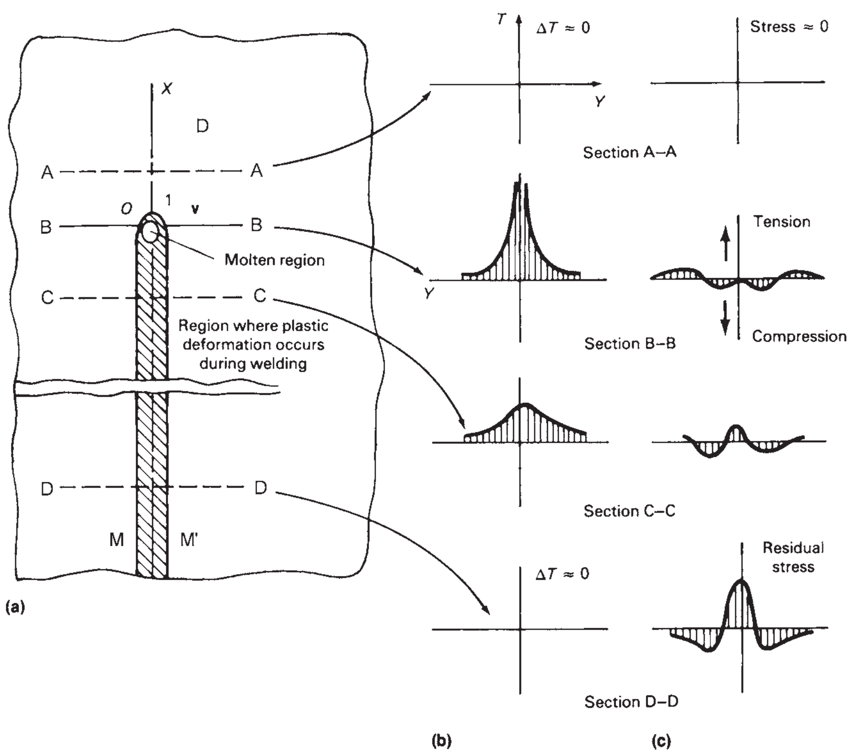


Fig. 5.11 Changes in temperature and stresses during welding: (a) weld, (b) temperature change, and (c) stress σ_x. Stress distribution is shown in the plane stress condition; therefore, stresses are regarded as being uniform in the thickness direction. Source: Ref 5.7

welding arc (section A–A), the slope of the temperature gradient due to welding ($\Delta T/\Delta Y$) is almost zero. However, along section B–B, which crosses the welding arc, the slope becomes very steep. Along section C–C, somewhat behind the welding arc, the slope becomes less steep. The slope of the temperature gradient due to welding once again approaches zero along section D–D, which is some distance behind the welding arc.

The distribution of normal stress in the x-direction (σ_x) along the cross sections is shown in Fig. 5.11(c). Normal stress in the y-direction (σ_y) and shearing stress (τ_{xy}) also exist in a two-dimensional stress field. In a three-dimensional stress field, six stress components exist: σ_x, σ_y, σ_z, τ_{xy}, τ_{yz}, and τ_{zx}. Figure 5.11(c) shows the distribution (along the y-axis) of normal stress in the x-direction (σ_x) due to welding (i.e., thermal stress). Along section A–A, the stresses are almost zero. The stress distribution along section B–B is complicated. Beneath the welding arc, stresses are close to zero, because molten metal does not support shear loading. Moving away from the arc, stresses become compressive, because expansion of the metal surrounding the weld pool is restrained by the base metal. Because the temperatures of these areas are quite high, the yield stress of the material becomes quite low. In other words, a situation occurs in which stresses in these areas are as high as the yield stress of the base metal at corresponding temperatures. The magnitude of compressive stress passes through a maximum with increasing distance from the weld or with decreasing temperature. However, stresses occurring in regions farther away from the welding arc are tensile in nature and balance with compressive stresses in areas near the weld pool.

Along section C–C, the weld metal and base metal regions have cooled (Fig. 5.11b). As they shrink, tensile stresses are caused in regions in and adjacent to the weld (Fig. 5.11c). As the distance from the weld increases, stresses become compressive. High tensile stresses exist along section D–D in and adjacent to the weld. Compressive stresses are produced in areas away from the weld.

Because of solidification shrinkage and thermal contraction of the weld metal during welding, the workpiece has a tendency to distort. Several types of weld distortions are illustrated in Fig. 5.12. The welded workpiece can shrink in the transverse direction (Fig. 5.12a) or in the longitudinal direction along the weld (Fig. 5.12b). Upward angular distortion usually occurs when the weld is made from the top of the workpiece alone (Fig. 5.12c): the weld tends to be wider at the top than at the bottom, causing more solidification shrinkage and thermal contraction at the top of the weld than at the bottom. In electron beam welding with a deep narrow keyhole, the weld is very narrow both at the top and the bottom, and there is little angular distortion. When fillet welds between a flat sheet at the bottom and a vertical sheet on the top shrink, they pull the flat sheet toward the vertical one and cause upward distortion in the flat sheet (Fig.

5.12d). The shrinkage and distortion that occur during fabrication of actual structures are far more complex than those shown in Fig. 5.12.

5.5 Distortion Control of Weldments

Proper use of preheat can minimize residual stresses and distortion that would normally occur during welding as a result of lower thermal gradients around the weld. Preheat also has the beneficial effect in steels of reducing the tendency for the formation of a large heat-affected zone (HAZ) and weld metal cracking.

Reducing the volume of the weld metal can reduce the amount of angular distortion and lateral shrinkage. The joint preparation angle and the root pass should be minimized, as shown in Fig. 5.13. The use of electron

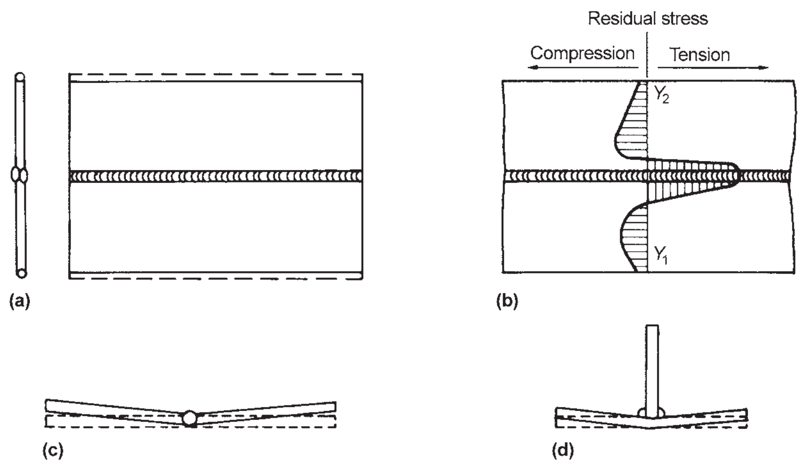


Fig. 5.12 Dimensional changes occurring in weldments: (a) transverse shrinkage in a groove weld, and (b) longitudinal shrinkage in a groove weld; and distribution of longitudinal residual stress: (c) angular change in a groove weld, and (d) angular change in a fillet weld. Source: Ref 5.7

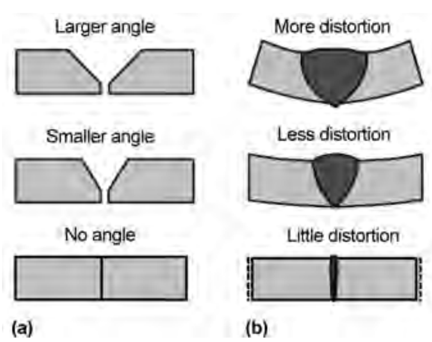


Fig. 5.13 Reducing angular distortion (a) by reducing volume of weld metal and (b) by using single-pass deep-penetration welding. Source: Ref 5.8, p 129

or laser beam welding that minimizes the HAZ can minimize angular distortion. Balancing welding by using a double-V joint in preference to a single-V joint can help reduce angular distortion. Welding alternately on either side of the double-V joint is preferred (Fig. 5.14). Placing welds about the neutral axis also helps reduce distortion. The shrinkage forces of an individual weld can be balanced by placing another weld on the opposite side of the neutral axis (Fig. 5.15). Two other techniques to reduce weld distortion are shown in Fig. 5.16. Presetting (Fig. 5.16a) is achieved by estimating the amount of distortion likely to occur during welding and then assembling the job with members preset to compensate for the distortion. Elastic prespringing (Fig. 5.16b) can reduce angular changes after the removal of the restraint. Preheating, thermal management during welding, and postweld heating can also reduce angular distortion.

Postweld heat treatment is often used to reduce residual stresses. Figure 5.17 shows the effect of temperature and time on stress relief in steel welds. Table 5.1 shows the temperature ranges used for postweld heat treatment of various types of steels, and Table 5.2 shows the weldability

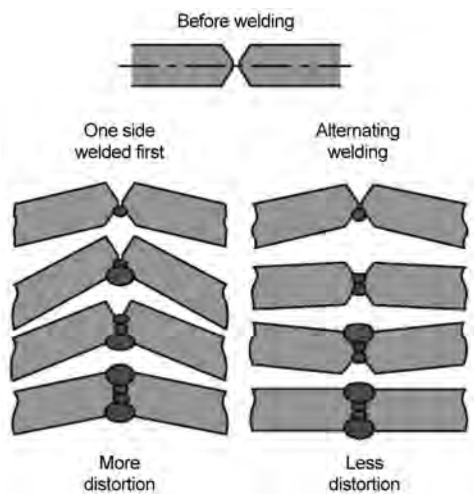


Fig. 5.14 Reducing angular distortion by using double-V joint and welding alternately on either side of joint. Source: Ref 5.8, p 129

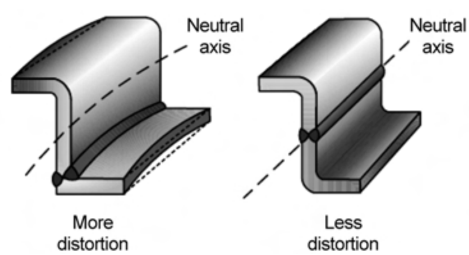


Fig. 5.15 Reducing distortion by placing welds around neutral axis. Source: Ref 5.8, p 129

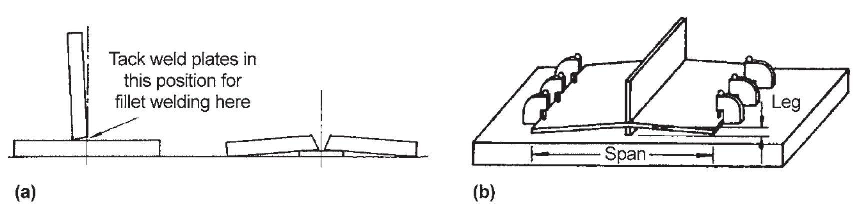


Fig. 5.16 Mechanical methods for controlling weld distortion: (a) presetting and (b) prespringing. Source: Ref 5.8, p 130

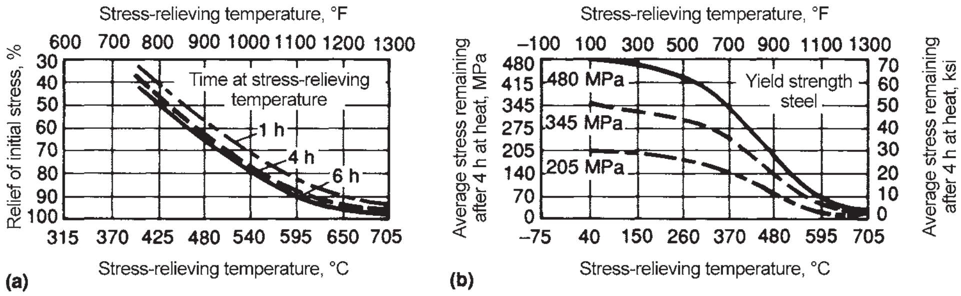


Fig. 5.17 Effect of temperature and time on stress relief. Source: Ref 5.7

Table 5.1 Typical thermal treatments for stress-relieving weldments

Material	Soak temperature, °C
Carbon steel	595–680
Carbon-1/2% Mo steel	595–720
1/2% Cr-1/2% Mo steel	595–720
1% Cr-1/2% Mo steel	620–730
1-1/4% Cr-1/2% Mo steel	705–760
2% Cr-1/2% Mo steel	705–760
2-1/4% Cr-1% Mo steel	705–770
5% Cr-1/2% Mo (type 502) steel	705–770
7% Cr-1/2% Mo steel	705–760
9% Cr-1% Mo steel	705–760
12% Cr (type 410) steel	760–815
16% Cr (type 430) steel	760–815
1-1/4% Mn-1/2% Mo steel	605–680
Low-alloy Cr-Ni-Mo steels	595–680
2-5% Ni steels	595–650
9% Ni steels	550–585
Quenched and tempered steels	540–550

Source: Ref 5.8

Table 5.2 Relative weldability of different families of steels

Plain carbon and low-alloy steels	Stainless steels
• Low carbon: 0.1–0.25% C Easily welded No preheat or postheat required • Medium carbon: 0.25–0.50% C Use low-hydrogen electrodes Preheat (300–500 °F) Temper • High carbon: 0.5–1.0% C Use low-hydrogen electrodes Preheat (400–600 °F) Temper • Low-alloy steels Q&T: 0.22% C max Use stringer bead technique Low-hydrogen electrodes No postheat required • Low-alloy steels: 0.25–0.45% C High-carbon martensite Use all crack-preventative methods Postweld heat treatment mandatory	• Austenitic: 200 and 300 series (18% Cr–8% Ni) Not hardenable by heat treatment Very weldable Chromium carbide formed at 800–1600 °F Use low-carbon or stabilized stainless • Ferritic: 405, 430, 446 (13–27% Cr) Poor weldability: brittle joints Low toughness and ductility Postweld anneal • Martensitic: 403, 410, 414, 420, 431, 440A, B&C (10–17% Cr) Weldable with precautions 0.1% C: no preheat 0.1–0.2% C: preheat to 500 °F, slow cool 0.2–0.5% C: preheat to 500 °F, anneal after welding • Precipitation hardened: martensitic (17-4 PH, 13-8 Mo, 15-5 PH) Very weldable, similar to austenitic Use austenitic filler if high strengths are not required Age single-pass welds to full strength Use compatible filler

of a number of steel and stainless steel families along with recommendations for preheating and postweld heat treatment.

5.6 Overview of Weld Discontinuities

Weld discontinuities are interruptions in the desirable physical structure of a weld. A discontinuity constituting a danger to a weld's fitness for service is a defect. By definition, a defect is a condition that must be removed or corrected. Neither construction materials nor engineered structures are free from imperfections, and welds and weld repairs are not exceptions. Weld acceptance standards are used when a discontinuity has been clearly located, identified, and sized, its orientation determined, and its structural significance questioned. Critical engineering assessments of weld discontinuities are performed to define acceptable, harmless discontinuities in a structure that will not sacrifice weldment reliability. One of the major reasons for understanding the engineering meaning of weld discontinuities is to decrease the cost of welded structures by avoiding unnecessary repairs of harmless weld discontinuities. The commonly encountered inclusions, as well as cracking, the most serious of weld defects, are discussed in this section.

5.6.1 Gas porosity

Gas porosity can occur on or just below the surface of a weld. Pores are characterized by a rounded or elongated teardrop shape with or without a sharp point. Pores can be uniformly distributed throughout the weld or isolated in small groups. They can also be concentrated at the root or toe of the weld. Porosity in welds is caused by gas entrapment in the molten metal, by too much moisture on the base or filler metal, or by improper cleaning of the joint during preparation for welding. The type of porosity within a weld is usually designated by the amount and distribution of the pores. Types include uniformly scatted porosity, cluster porosity, linear porosity, elongated porosity, and wormhole porosity. Radiography is the most widely used nondestructive method for detecting subsurface gas porosity in weldments.

5.6.2 Slag Inclusions

Slag inclusions can occur when using welding processes that employ a slag covering for shielding purposes. With other processes, the oxide present on the metal surface before welding may also become entrapped. Slag inclusions can be found near the surface and in the root of a weld (Fig. 5.18a), between weld beads in multipass welds (Fig. 5.18b), and at the side of a weld near the root (Fig. 5.18c).

During welding, slag may spill ahead of the arc and subsequently be covered by the weld pool because of poor joint fit-up, incorrect electrode

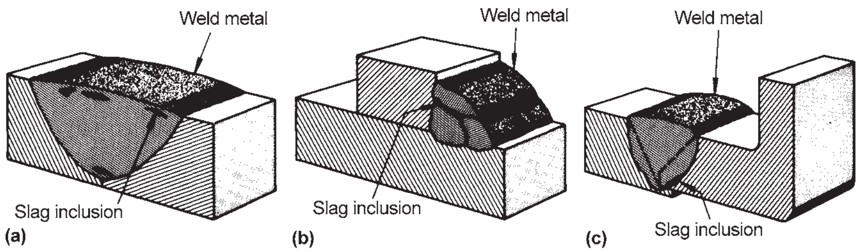


Fig. 5.18 Locations of slag inclusions in weld metal: (a) near the surface and in the root of a single-pass weld, (b) between weld beads in a multipass weld, and (c) at the side of a weld near the root. Source: Ref 5.9

manipulation, or forward arc blow. Slag trapped in this manner is generally located near the root. Radical motions of the electrode, such as wide weaving, may also cause slag entrapment on the sides or near the top of the weld after the slag spills into a portion of the joint that has not been filled by the molten pool. Incomplete removal of the slag from the previous pass in multipass welding is another common cause of entrapment. In multipass welds, slag may be entrapped any number of places in the weld between passes. Slag inclusions are generally oriented along the direction of welding. Three methods used for the detection of slag below the surface of single-pass or multipass welds are magnetic particle, radiographic, and ultrasonic inspection.

5.6.3 Tungsten Inclusions

Tungsten inclusions are particles found in the weld metal from the nonconsumable tungsten electrode used in gas tungsten arc welding. These inclusions are the result of:

- Exceeding the maximum current for a given electrode size or type
- Letting the tip of the electrode make contact with the molten weld pool
- Using an excessive electrode extension
- Inadequate gas shielding or excessive wind drafts that result in oxidation
- Using improper shielding gases such as argon-oxygen or argon-CO_2 mixtures, which are used for gas metal arc welding

Tungsten inclusions, which are not acceptable for high-quality work, can be found only by internal inspection techniques, particularly radiographic testing. In general, they must be ground out and repair welded.

5.6.4 Lack of Fusion and Lack of Penetration

Lack of fusion and lack of penetration result from improper electrode manipulation and the use of incorrect welding conditions. Fusion refers to the degree to which the original base metal surfaces to be welded have been fused to the filler metal. Penetration refers to the degree to which the base metal has been melted and resolidified to result in a deeper throat than that was present in the joint before welding. In effect, a joint can be completely fused but have incomplete root penetration to obtain the throat size specified. Based on these definitions, lack-of-fusion discontinuities are located on the sidewalls of a joint, and lack-of-penetration discontinuities are located near the root (Fig. 5.19). With some joint configurations, such as butt joints, the two terms can be used interchangeably. The causes of lack of fusion include excessive travel speed, bridging, excessive electrode size, insufficient current, poor joint preparation, overly acute joint angle, improper electrode manipulation, and excessive arc blow. Lack of penetration can be the result of low welding current, excessive travel speed, improper electrode manipulation, or surface contaminants such as oxide, oil, or dirt that prevent full melting of the underlying metal.

Radiographic methods may be unable to detect these discontinuities in certain cases, because of the small effect they have on x-ray absorption. However, lack of sidewall fusion is readily detected by radiography. Ultrasonically, both types of discontinuities often appear as severe, almost continuous, linear porosity because of the nature of the unbonded areas of the joint. Except in thin sheet or plate, these discontinuities may be too deep to be detected by magnetic particle inspection.

5.6.5 Geometric Weld Discontinuities

Geometric weld discontinuities (Fig. 5.20) are those associated with imperfect shape or unacceptable weld contour. Undercut, underfill, overlap, excessive reinforcement, fillet shape, and melt-through are included in this grouping. Visual inspection and radiography are most often used to detect these flaws.

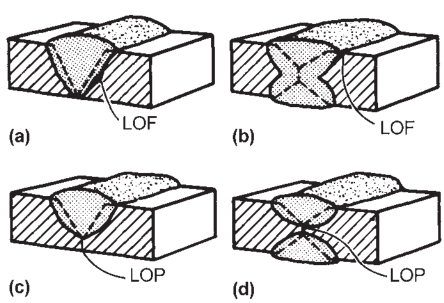


Fig. 5.19 Lack of fusion (LOF) in (a) a single-V groove weld, and (b) double-V groove weld, and lack of penetration (LOP) in (c) a single-V groove weld, and (d) a double-V groove weld. Source: Ref 5.9

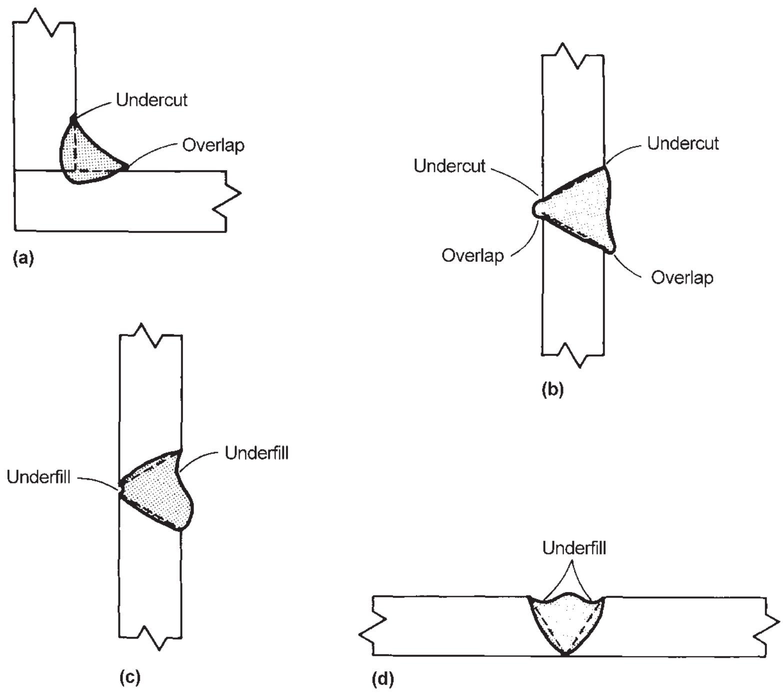


Fig. 5.20 Weld discontinuities affect weld shape and contour: (a) undercut and overlapping a fillet weld, (b) undercut and overlapping in a groove weld, and (c) and (d) underfill in groove welds. Source: Ref 5.9

5.6.6 Cracking Associated with Welding

Four types of cracking are a concern in welded structures: hot cracks, heat-affected zone (HAZ) microfissures, cold cracks, and lamellar tearing.

Solidification Cracking (Hot Cracking). Hot cracks are solidification cracks that occur in the fusion zone near the end of solidification. They result from the inability of the semisolid material to accommodate the thermal shrinkage strains associated with weld solidification and cooling. Cracks then form at susceptible sites to relieve the accumulating strain. Susceptible sites are interfaces, such as solidification grain boundaries and interdendritic regions, that are at least partially wetted.

Solidification cracking requires both a sufficient amount of mechanical restraint (strain) and a susceptible microstructure. Under conditions of rapid solidification and cooling, the rate of strain accumulation is rapid, leading to an increased cracking susceptibility. Inherently, then, requisite strains for solidification cracking are more likely to be experienced with welding processes that promote rapid solidification and cooling. The use of preheating and controlled heating and cool-down rates helps to prevent hot cracking.

The approach used to minimize the mechanical factor is to reduce the overall weld restraint through joint design and appropriate choice of welding parameters. A simple way to minimize the restraint on a solidifying weld joint is to keep the joint gap to a minimum by designing hardware with good fit-up. Welding parameters can have a profound influence on the occurrence of solidification cracking. The natural tendency to use high-speed welding to improve productivity can have detrimental effects. Formation of a teardrop-shaped weld pool, which may occur as the weld travel speed increases, can result in centerline solidification cracks. The solidification pattern associated with this type of weld pool is such that solidifying grains meet at the weld centerline, forming a particularly susceptible site for solidification crack initiation.

Alloys with a wide solidification temperature range are more susceptible to solidification cracking than are alloys that solidify over a narrow temperature range. This occurs because accumulated thermal strain is proportional to the temperature range over which a material solidifies. Composition effects in steel alloys that can cause hot cracking include high carbon contents, high alloy contents, and high sulfur contents. Manganese additions are frequently used to tie up sulfur in the form of harmless globular MnS particles.

Heat-Affected Zone Cracks. Microfissures are cracks that occur in the area of partial melting and the HAZ adjacent to the fusion line. Microfissures often occur as a result of local chemical variations in the metal that result in local variations in the melting point. Segregation of specific alloying elements to grain boundaries may cause a reduction in the melting temperatures of these areas. During fusion welding, this manifests in the formation of a zone of partial melting at temperatures below the alloy liquidus.

Many microfissures form in a manner somewhat analogous to the formation of solidification cracks in that susceptible sites, generally grain boundaries that intersect the fusion zone, are wetted with liquid from one of various sources. Shrinkage strains accumulating as the weld pool advances past the liquated boundary can develop to a level sufficient to cause boundary separation (i.e., cracking). Figure 5.21 is a photomicrograph of an HAZ microfissure in cast austenitic stainless steel. (This crack also extends into the fusion zone as a solidification crack.) Cast microstructures are highly inhomogeneous, raising the possibility of extensive partial melting. Note the melting associated with interdendritic constituents in Fig. 5.21.

The presence of a liquid is not essential to the formation of HAZ cracks, because they may occur at temperatures well below the solidus. Poor ductility inherent in certain materials, such as intermetallics, can lead to solid-state failure during welding if the thermal stresses associated with the weld thermal cycle exceed the local tensile strength. Cracks can also occur in alloys that undergo phase transformations during the weld thermal

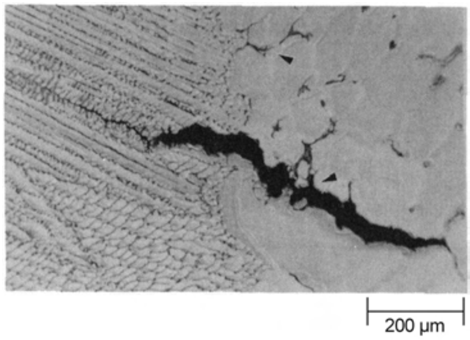


Fig. 5.21 HAZ microfissure in cast stainless steel. Note extensive region of partial melting. Source: Ref 5.10

cycle. The act of fusion welding subjects the fusion zone and the HAZ to temperatures above those normally encountered during prior deformation processing. The resultant HAZ microstructure may differ substantially from that of the base material. If the newly transformed microstructure has limited ductility, which is not uncommon in shear transformations or in transformations that result in ordered structures, the likelihood of cracks forming at susceptible sites, such as grain boundaries, matrix/minor phase interfaces, and slip band intersections, is increased.

Reheat cracking, also referred to as stress-relief or strain-age cracking, is another defect type observed in certain alloys that undergo precipitation reactions. Historically observed in several nickel-based superalloys and creep-resistant steels, this type of defect manifests during postweld heat treatment, generally as intergranular HAZ cracks. Postweld heat treatment is often a recommended practice for high-strength thick-section welded steels, where a reduction of residual stresses developed as a result of welding is desired. In the case of welded nickel-based superalloys, postweld heat treatment is used both to relieve residual stresses and to achieve optimum mechanical properties through precipitation hardening reactions.

In alloys that undergo precipitation reactions, the rate at which the alloy strengthens may greatly exceed the rate at which residual stresses are thermally diminished. This can be especially true in the case of heavy-section welds or in alloys with relatively poor thermal conductivity. That is, before the alloy can reach the temperature at which residual stresses begin to be eliminated, it has aged and lost ductility relative to its as-welded state. At this new lower level of ductility, the residual stresses present may induce cracks to eliminate the accumulated strain energy. In principle, the problem of reheat cracking could be largely eliminated if the rate of heating through the precipitation temperature range was rapid enough to prevent precipitate formation. However, extremely rapid rates of heating in welded hardware would likely lead to problems such as excessive distortion; therefore, improved alloys (e.g., alloy 718 among the superalloys) have been developed in which the kinetics of precipitate formation have been sufficiently retarded to allow for successful postweld heat treatment.

Hydrogen-Induced Cracking (Cold Cracking). Cold cracks are defects that form as the result of the contamination of the weld microstructure by hydrogen. Whereas solidification cracking and HAZ cracking occur during or soon after the actual welding process, hydrogen-induced cracking is usually a delayed phenomenon, occurring possibly weeks or even months after the welding operation. The temperature at which these defects tend to form ranges from –50 to 150 °C (–60 to 300 °F) in steels. The fracture can be either intergranular or transgranular cleavage.

As with other forms of cracking, hydrogen-induced cracking involves both a requisite microstructure and a threshold level of stress. It also involves a critical level of hydrogen, which depends on the alloy and microstructure. In the case of ideal weld processing, hydrogen-induced cracking would be at most a minor welding engineering concern. However, excluding hydrogen from structures during welding is exceedingly difficult. Although the primary source of hydrogen in weld metal is considered to be the disassociation of water vapor in the arc and absorption of gaseous or ionized hydrogen into the liquid, other sources are also available. All organic compounds contain hydrogen in their molecular structure, and all may be broken down in the intense thermal environment of a welding heat source. Organic compounds are ubiquitous in the welding environment, from lubricants in assembly areas to body oils on the hands of welding operators. Plated hardware may also contain high levels of residual hydrogen.

The mechanism of hydrogen-induced crack formation is still being investigated. The most widely accepted model involves the presence of preexisting defect sites in the material—small cracks or discontinuities caused by minor phase particles or inclusions. In the presence of existing stress, these sites may develop high local areas of biaxial or triaxial tensile stress. Hydrogen diffuses preferentially to these sites of dilated lattice structure. As the local hydrogen concentration increases, the cohesive energy and stress of the lattice decrease. When the cohesive stress falls below the local intensified stress level, fracture occurs spontaneously. Hydrogen then evolves in the crack volume, and the process is repeated. This model of hydrogen-induced cracking is consistent with the relatively slow and discontinuous nature of the process.

In steels, where the problem of hydrogen-induced cracking is significant, cracking susceptibility has been correlated both with material hardness and strength and with specific microstructure. Higher-strength steels are more susceptible to hydrogen-induced cracking than are low-strength steels. Steels that transform martensitically are particularly susceptible, especially the higher-carbon alloys with twinned martensitic structures. The desire to avoid martensite formation has driven the development of high-strength structural steels for welded applications. Production of the newer high-strength low-alloy (HSLA) steels uses a variety of precisely controlled alloying additions (e.g., aluminum, titanium, vanadium, and niobium) along with meticulous thermomechanical processing to develop a very fine-grained ferrite microstructure possessing substantial strength and fracture toughness with a high degree of resistance to hydrogen-induced cracking.

A useful concept for understanding the susceptibility of carbon and alloy steels to hydrogen-induced cracking is the carbon equivalent (CE), an empirical relationship that attempts to reduce the number of significant compositional variables affecting the weldability of steels into a single quantity. Several CE relationships have been developed for different classes of steels. An example is:

$$\mathrm{CE} = \%\mathrm{C} + \frac{\%\mathrm{Mn}}{6} + \frac{\%\mathrm{Cr} + \%\mathrm{Mo} + \%\mathrm{V}}{5} + \frac{\%\mathrm{Si} + \%\mathrm{Ni} + \%\mathrm{Cu}}{15} \qquad \text{(Eq 5.1)}$$

From a metallurgical perspective, the CE can be related to the development of hydrogen-sensitive microstructures. That is, as the CE increases, microstructures are evolved during cooling through the transformation temperature range that are increasingly more susceptible to hydrogen-induced cracking. At high CE values, martensitic structures can be expected. In Eq 5.1, when the CE exceeds 0.35%, preheats are recommended to minimize susceptibility to hydrogen cracking. At higher levels of CE, both preheats and postheats may be required.

The following guidelines should be followed to minimize the occurrence of hydrogen-induced cracking. For a given level of required strength, the steel with the lowest CE should be considered. Low-hydrogen welding practices should be followed. This involves elimination of possible sources of hydrogen by using ultrahigh-purity gases and moisture-free gas lines and by baking coated electrodes, following the manufacturer's recommendations, to ensure removal of nascent water. Finally, preheating and postheating requirements should be used.

Lamellar Tearing. Lamellar tearing is cracking that occurs beneath welds. It is found in rolled steel plate weldments. The tearing always lies within the base metal, generally outside the HAZ and parallel to the weld fusion boundary. The problem is caused by welds that subject the base metal to tensile loads in the *z*- or through-direction of the rolled steel. Occasionally the tearing comes to the surface of the metal, but more commonly it remains under the weld (Fig. 5.22) and is detectable only by ultrasonic testing. Lamellar tearing occurs when three conditions are simultaneously present:

- Strains develop in the through-direction of the plate. They are caused weld metal shrinkage in the joint and can be increased by residual stresses and by loading.

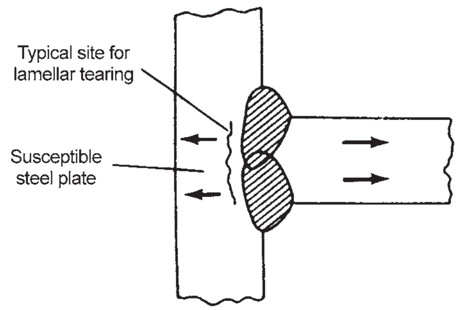


Fig. 5.22 Typical location for lamellar tearing in a T-joint. Source: Ref 5.10

- The weld orientation is such that the stress acts through the joint across the plate thickness (the *z*-direction). The fusion line beneath the weld is roughly parallel to the laminar separation.
- The material has poor ductility in the *z*-direction.

The problem can be avoided by proper attention to joint details. In T-joints, double-fillet welds appear to be less susceptible than full-penetration welds. Also, balanced welds on both sides of the joint appear to present less risk than large, single-sided welds.

5.7 Fatigue of Weldments

An examination of structural and component failures documented in the literature over the past 50 years clearly indicates that failures predominantly start at joints, especially at welded joints. A weld can introduce many detrimental features, including changes in the microstructure and mechanical properties, introduction of welding residual stresses, and the introduction of weld imperfections. In welded structures, fatigue cracking is by far the most common failure mechanism. As shown in Fig. 5.23, attaching a weld to a load-carrying member not only reduces the fatigue strength substantially but also lowers the fatigue limit. In this example, the fatigue limit of the welded component is one-tenth of that of the plain component. As a consequence, in cyclically loaded welded components the design stresses are frequently limited by the fatigue strength of the welded joints.

A weld reduces the fatigue strength of a component for several reasons, categorized as:

- Stress concentration due to weld shape and joint geometry
- Stress concentration due to weld imperfections
- Residual welding stresses

To design against fatigue in welded structures, it is important to understand the influence of these factors on the performance of welded joints.

5.7.1 Stress Concentration Due to Weld Shape and Joint Geometry

Making a welded joint either increases or decreases the local cross-section dimensions where the parent metal meets the weld. Generally, any change in cross-section dimensions in a loaded member will lead to a stress concentration. Thus, it is inevitable that the introduction of a weld will produce an increase in the local stress. The precise location and the magnitude of stress concentration in welded joints depend on the design of the joint and the direction of the load. Some examples of stress concentrations in butt welds and fillet welds are shown in Fig. 5.24. The weld toe is often the primary location for fatigue cracking in joints that have good

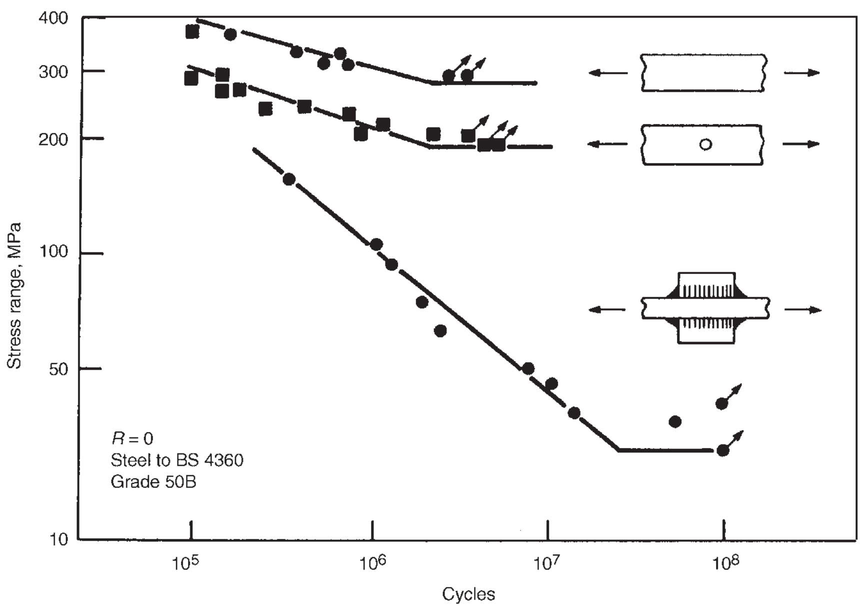


Fig. 5.23 Comparison of fatigue behavior: parent metal, parent metal with a hole, and a welded joint. Source: Ref 5.11

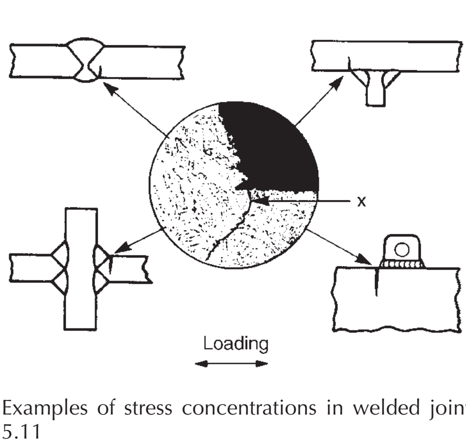


Fig. 5.24 Examples of stress concentrations in welded joints. Source: Ref 5.11

root penetration. In situations where the root penetration is poor or the root gap is excessive, or in load-carrying fillet welds where the weld throat is insufficient, the root area can become the region of highest stress concentration. Fatigue cracks in these situations start from the root of the weld and generally propagate through the weld. In general, the fatigue strength of a welded joint decreases with increasing attachment length, increasing plate thickness, increasing weld angle, decreasing toe radius, and misalignment.

5.7.2 Stress Concentration Due to Weld Discontinuities

Stress analysis of an idealized model of a fillet weld loaded in the transverse direction has shown that the stress concentration factor (K_t) at the weld toe is about 3. This is comparable to K_t for a hole in a plate. Therefore, it would be reasonable to expect that the fatigue behavior of a fillet weld would be similar to that of a plate with a hole. However, as shown in Fig. 5.23, the fatigue performance of the welded joint is substantially lower, implying that other factors come into play for welded joints. This difference has been attributed to the presence of microscopic features at the weld toe. These features are small, sharp nonmetallic intrusions that are present in most if not all welds. The extent and distribution of these features vary with the welding process, and also possibly with the quality of the steel plate and its surface condition. The exact source of these intrusions is not precisely known, but it is believed that slag, surface scale, and nonmetallic stringers from dirty steel are the primary causes. Figure 5.25 shows an example of weld toe intrusions. The combined effect of these sharp cracklike features and concentration of stress due to the weld geom-

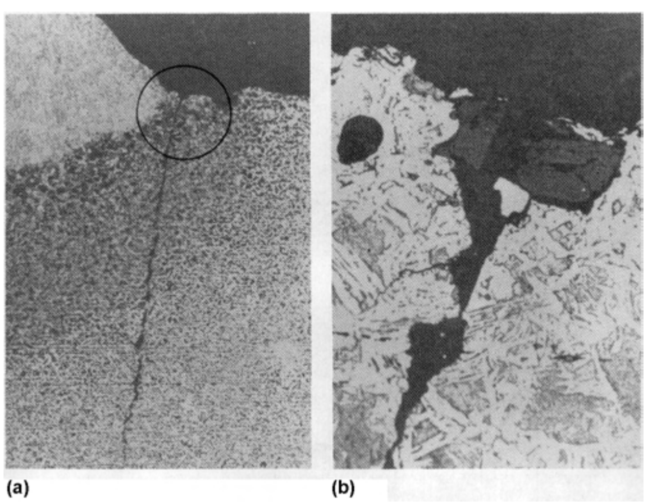


Fig. 5.25 Example of weld toe intrusions. Source: Ref 5.11

etry is that fatigue cracks initiate very early on, and most of the fatigue life is spent in crack propagation.

Planar weld imperfections (e.g., hydrogen cracks, lack of sidewall fusion) are clearly to be avoided because they will substantially reduce fatigue life. However, volumetric imperfections such as slag inclusions and porosity can be tolerated to some extent, because the notch effect of these imperfections is generally lower than that of the weld toe (Fig. 5.26).

5.7.3 Residual Welding Stresses

As previously discussed, residual stresses are normally present in the weldment area, and these can be high and even approach the yield strength. These stresses occur as a result of: (a) thermal expansion and contraction during welding, (b) the constraint provided by the fabrication or by the fixtures, and (c) distortion in the structure during fabrication. These stresses are localized to the weld zone and are self-balancing; that is, both tensile and compressive stresses are present. Transverse to the weld toe, the residual stress is typically tensile and can approach the yield point. When a tensile load cycle is applied to the structure, it is superimposed onto the residual stress field, leading to higher overall stresses.

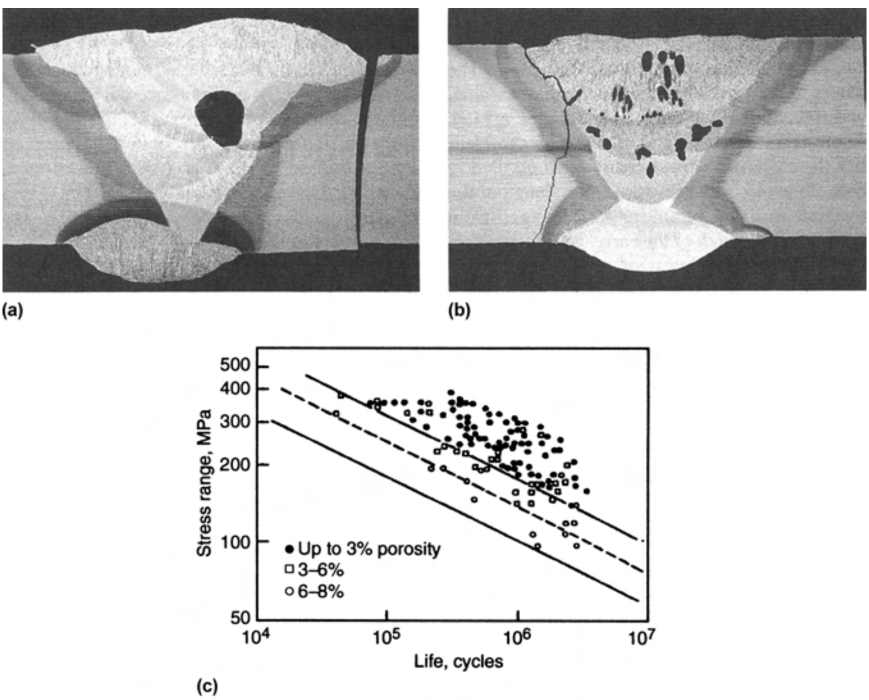


Fig. 5.26 Effect of volumetric defects on fatigue: (a) slag inclusion in butt weld, and cracking from weld toe; (b) porosity in butt weld, and cracking from weld toe; and (c) transverse groove welds containing porosity. Source: Ref 5.11

Reducing residual stresses using postweld heat treatment can improve fatigue life, but only if the applied load cycles are partially or fully compressive. For fully tensile-applied loads, postweld heat treatment does not improve fatigue life. Thus, it is important to know the exact nature of applied loads before a decision is made on the need to heat treat a welded structure. Indeed, stress relief of welded joints is never fully effective. Residual stresses up to yield point have been measured in stress-relieved pressure vessels and in up to 75% of yield in stress-relieved nodes in offshore structures. Due consideration has to be given to the complexity of the overall structure when stress relieving and to the time and temperature of the process.

Because crack propagation dominates the fatigue life of welded joints, material properties have no effect on fatigue strength. In Fig. 5.27, data points for steels with different strengths fall within the same scatter band. Thus, using a higher-strength steel to improve fatigue life will not be beneficial for welded structures.

5.7.4 Methods for Improving the Fatigue Life of Welded Joints

As described in the preceding sections, three factors influence fatigue of welded joints: stress concentration due to joint and weld geometry, stress concentration due to localized defects, and welding residual stresses. Improvement in fatigue life can be obtained by reducing the effects of one or more of these parameters. This is particularly true for cracks starting

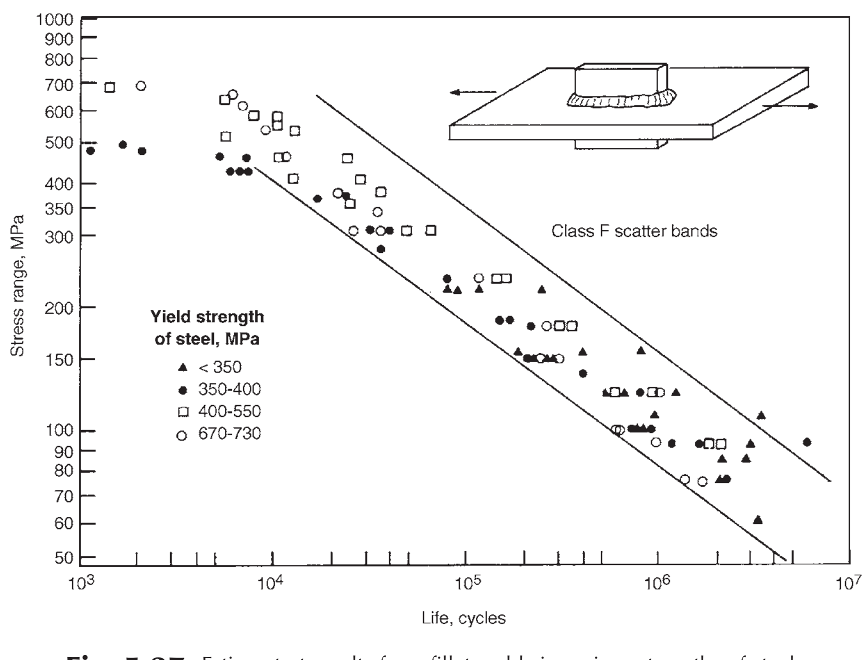


Fig. 5.27 Fatigue test results from fillet welds in various strengths of steel. Source: Ref 5.11

from the weld toe, which is by far the most common failure site. In load-carrying fillet welds, however, cracks can start at the weld root and propagate through the weld throat until failure occurs. In this case, additional weld metal to increase the weld throat dimension will result in a reduction in shear stresses and, hence, a corresponding increase in fatigue strength.

Because the most common failure site is the weld toe, many postweld treatments for this region have been developed to improve the fatigue life. These techniques largely rely on removing the detrimental intrusions at the weld toe, reducing the joint stress concentration, or modifying the residual stress distribution. There are primarily two broad categories of postweld techniques: modification of the weld geometry and modification of the residual stress distribution. Methods that reduce the severity of the stress concentration or remove weld toe intrusions include grinding, machining, or remelting. These techniques essentially focus on altering the local weld geometry by removing the intrusions and at the same time on achieving a smooth transition between the weld and the plate. Because weld toe intrusions can be up to 0.4 mm (0.016 in.) in depth, the general guideline is that the grinding or machining operation must penetrate at least 0.5 mm (0.02 in.) into the parent plate. In these procedures the depth, the diameter of the groove, and the direction of the grinding marks become important issues. In gas tungsten arc and plasma dressing, the weld toe is remelted to improve the local profile and also to “burn” away or move the intrusions. With these techniques, the positions of the arc with respect to the weld toe and the depth of the remelt zone are two critical variables. Controlling the shape of the overall weld profile has also been recognized as a method of improving the fatigue life.

Methods that modify the residual stress field include heat treatment, hammer and shot peening, and overloading. Postweld heat treatment is known to reduce tensile residual stresses but does not eliminate them completely. The benefits of postweld heat treatment can be realized only if the applied loads are either partially or fully compressive. Overloading techniques rely on reducing the tensile residual stress field and/or introducing compressive stresses at the weld toe. Exact loading conditions for a complex structure are difficult to establish, so this technique is rarely used. To obtain significant improvement in fatigue strength, it is necessary to introduce compressive stresses in the local area in a consistent and repeatable manner. The three peening techniques (shot, needle, and hammer peening) aim to achieve this by cold working the surface of the weld toe. As with the grinding methods, it is necessary to penetrate the parent plate and deform to a depth of ≥0.5 mm (0.02 in.). Hammer peening is perhaps the best technique to do this, and it has the advantage of removing the weld toe intrusions by cold working them out. Peening techniques require special equipment and can present safety challenges for noise control. They are also very difficult to automate and control in production.

A comparison of the improvement in fatigue strength obtained by some of these techniques is shown in Fig. 5.28. Hammer peening is perhaps the best technique, because it reduces or eliminates intrusions as well as introducing compressive stresses. Burr grinding, which is easier to implement, also produces significant improvement in fatigue life. Disk grinding and burr grinding are probably the most frequently used methods for improving the fatigue life of welded joints.

5.8 Characterization of Welds

Inspection and characterization of welds may be nondestructive or destructive. Nondestructive techniques include visual, liquid penetrant, magnetic particle, radiographic, and ultrasonic methods. Destructive procedures require the removal of specimens from the weld. The first destructive procedure is macrostructural characterization of a sectioned weld, including features such as number of passes; weld bead size, shape, and homogeneity; and the orientation of beads in a multipass weld. Macroscopic characterization is followed by microstructural analysis, including microsegregation, grain size and structure, the phase makeup of the weld, and compositional analysis. Destructive procedures may also include the measurement of mechanical and corrosion properties. The goal of any weld is to create a structure that can meet all the demands of its service environment. In many cases, the best way to assess the performance of a weld is to establish its mechanical properties. In addition to a number of

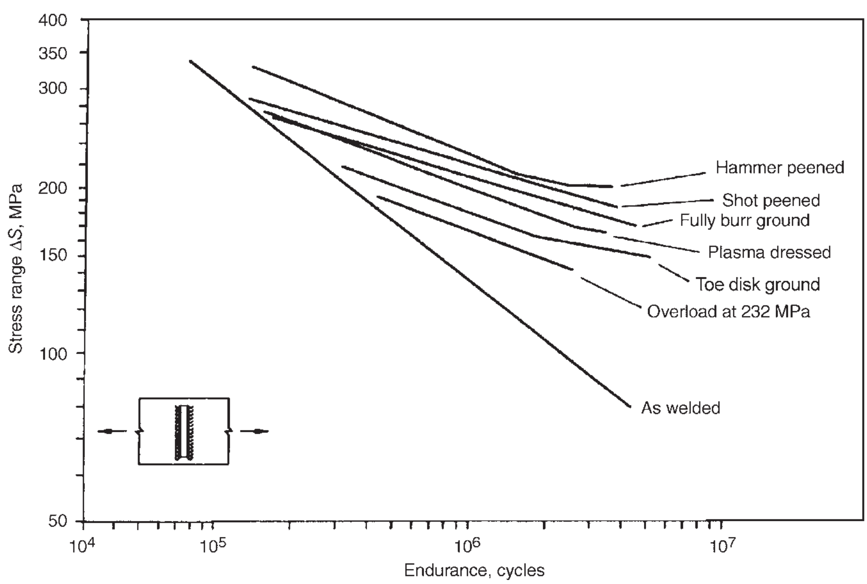


Fig. 5.28 Comparison of different postweld fatigue improvement techniques. Source: Ref 5.11

standard material tests, many mechanical tests are directed specifically at determining a weld's capabilities. Examples of mechanical properties typically characterized for welds include yield and tensile strength, ductility, hardness, and impact or fracture toughness. Corrosion testing is often employed in situations where a welding operation is performed on a corrosion-resistant material or in a structure exposed to a hostile environment. Although absolute corrosion performance is important, a major concern is to ensure that a weld and its heat-affected zone (HAZ) are cathodic to the surrounding metal.

5.8.1 Visual Inspection

Several factors associated with the production and performance of welds are macroscopic and easily observed. The most obvious of these are the size, shape, and general appearance of the weld. To a large extent, these parameters depend on the geometry of the weld joint and the welding process selected. A number of general considerations apply to most types of welds:

- *Size:* The size of the weld should be appropriate for the part. As an example, a general rule for fillet welds is that the ratio of leg size to plate thickness should be between 3 to 4 and 1 to 1.
- *Location:* An incorrectly located butt weld may not allow the part to function properly. A less extreme example is a fillet weld with uneven leg lengths, leading to an uneven stress distribution and perhaps laminar tearing.
- *Uniformity:* Distortion, the probability of slag entrapment on multipass welds, and uniformity of load-carrying ability all depend on the relative uniformity of the weld.
- *Defects:* Ideally, a weld should be free of macroscopic defects. Common visual defects include undercutting, lack of fusion, pinhole porosity, and slag entrapment.
- *Face shape:* A weld should have a relatively flat face. If the weld is too convex, stress will be concentrated along the toe of the weld. Conversely, a high concave weld face will result in locally high stresses in the throat region of the weld.

5.8.2 Nondestructive Inspection

The most common of nondestructive methods used as assess welds are liquid penetrant inspection, magnetic particle inspection, radiography, and ultrasonic inspection. The characteristics of these nondestructive inspection techniques are given in Table 5.3.

Liquid penetrant inspection involves the application of an indicator fluid that has a surface tension sufficiently low to be drawn into surface cracks too small to be detected visually. The excess dye or fluorescent

Table 5.3 Guidelines for selecting nondestructive testing techniques

Technique	Equipment requirements	Defects detected	Advantages	Limitations	Comments
Liquid-penetrant or fluorescent-penetrant inspection	Fluorescent or visible penetration liquids and developers; ultraviolet light for fluorescent dyes	Defects open to the surface only; good for leak detection	Detects small surface imperfections; easy application; inexpensive; use on magnetic or nonmagnetic material	Time-consuming; not permanent	Used on root pass of highly critical pipe welds; indications may be misleading on poorly prepared surfaces
Magnetic particle inspection	Wet or dry iron particles, or fluorescent; special power source; ultraviolet light for fluorescent dyes	Surface and near-surface discontinuities: cracks, porosity, slag	Indicates discontinuities not visible to the naked eye: useful for checking edges before welding: no size limitations	For magnetic materials: surface roughness may distort magnetic field; not permanent	Test from two perpendicular directions to detect any indications parallel to one set of magnetic lines
Radiographic inspection	Equipment for x-ray or γ-ray; film processing and viewing	Most internal discontinuities and flaws; limited by direction of discontinuity	Provides permanent record of surface and internal flaws; applicable to any alloy	Usually not suitable for fillet weld inspection; film exposure and processing critical; slow and expensive	Popular technique for subsurface inspection
Ultrasonic inspection	Ultrasonic units and probes; reference patterns	Can locate all internal flaws located by other methods, as well as small flaws	Extremely sensitive: complex weldments restrict usage: can be used on all materials	Highly skilled interpretor required; not permanent	Required by some specifications and codes

Source: Ref 5.12

material is then removed from the surface, but it remains in and highlights the cracks when a developer is applied.

Magnetic particle inspection is a method of locating surface and subsurface discontinuities in ferromagnetic materials. It depends on the fact that when the material or part under test is magnetized, magnetic discontinuities that lie in a direction generally transverse to the direction of the magnetic field will cause a leakage field to be formed at and above the surface of the part. The presence of this leakage field, and therefore the presence of the discontinuity, is detected by the use of finely divided ferromagnetic particles applied over the surface, with some of the particles being gathered and held by the leakage field. This magnetically held collection of particles forms an outline of the discontinuity and generally indicates its location, size, shape, and extent. Magnetic particles are applied over a surface as dry particles, or as wet particles in a liquid carrier such as water or oil.

Radiography is used to detect internal defects such as porosity or inclusions. These defects show up because of the difference in x-ray absorption between the matrix and defect materials. Although a number of factors affect the resolution level of radiographic techniques, the minimum size of defects considered in American Welding Society (AWS) specifications is 0.4 mm (0.0156 in.). In practice, this refers to slag entrapment and large inclusions that were present in the starting material. Defect structures are usually quantified by comparison with an existing standard, several of which exist.

Ultrasonic testing can also be used to locate internal defects, including porosity and inclusions. Ultrasonic testing involves transmitting mechanical vibrations through a piece of metal and analyzing both reflected and transmitted vibrations (Fig. 5.29). Vibrations interact with discontinuities in the media through which they are passing, so the operator can detect voids, inclusions, and other internal interfaces.

5.8.3 Microstructural Characterization

Weld microstructures are examined using standard specimen removal and preparation techniques, with some concessions made for their inhomogeneous nature. Similarly, the parameters used to characterize the weld microstructures, such as grain size, grain morphology, and the amount of the various phases or microconstituents present, are the same as those used to characterize monolithic materials.

These procedures are usually based on a cross section of the weld, referred to as a transverse section. In Fig. 5.30, (a) and (b) show transverse sections of two multipass welds, a submerged arc weld made on 25 mm (1 in.) thick ASTM A36 steel and a flux-cored weld made on 50 mm (2 in.) thick ASTM A537 steel. Readily apparent features include the number of passes and number of layers, fusion zone area, weld aspect ratio, extent of penetration, face width, and the reinforcement and curvature of the top bead. A transverse section will also show any gross porosity or large inclusions present in a weld and the extent of the HAZ.

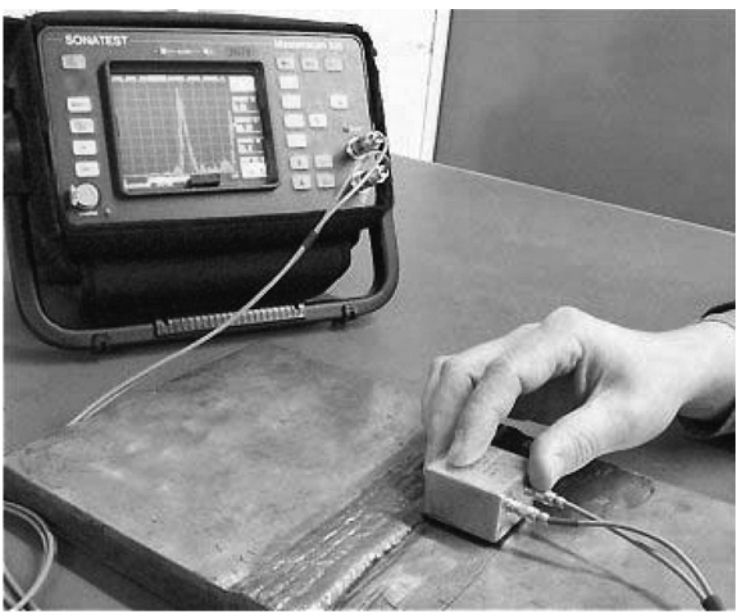
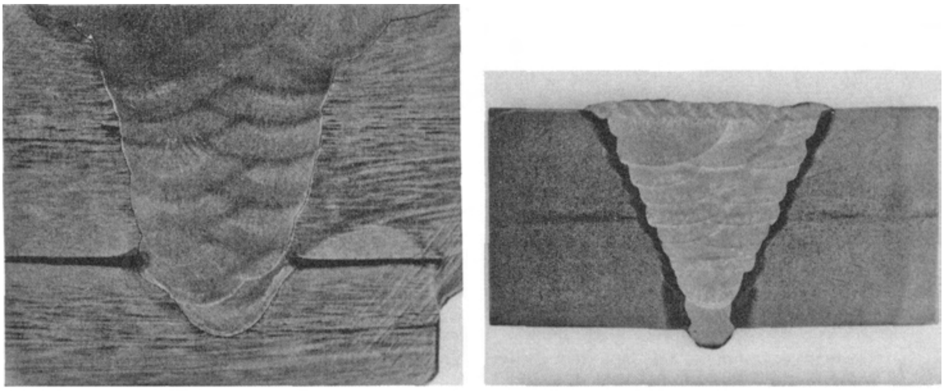


Fig. 5.29 Ultrasonic inspection of a weldment



(a) (b)

Fig. 5.30 Typical multipass arc welds in steels used in structural applications: (a) submerged arc weld on 25 mm (1 in.) thick A36 structural steel—the mushroom shape of the last weld bead is typical of welds made by this process; (b) flux-cored arc weld on 50 mm (2 in.) thick A537 steel used in pressure vessel and structural applications—the last layer was made with several small passes to improve mechanical properties. Source: Ref 5.12

One common use of hardness values in weld specifications is as a check for the formation of microstructures that might have low ductility and toughness and thus are prone to cracking. For example, in pipeline steels, the formation of martensite in the HAZ is a cause for concern because of the potential for cracking. This is addressed by specifying maximum values for microhardness traverses across several sections of the weld. Hardness values are also used as an indicator of susceptibility to some forms of stress-corrosion cracking.

5.8.4 Mechanical Testing

A number of mechanical properties are used to characterize welds, including strength, ductility, hardness, and toughness. In general, the samples and procedures are the same as those used in other areas of metallurgy. However, a prominent concern regarding the mechanical performance of welds is the direct comparison with the base material. The goal is to ensure that the weld is not the weakest component of a structure or, if it is, to compensate for this in the design.

Yield and tensile strength are measured for all-weld-metal specimens using a standard tensile test but with specimens removed from test plates welded according to AWS-specified procedures. These tests form the basis for the assignment of yield and ultimate strength values to welds made using a specific electrode and according to a set procedure. Additional tests are sometimes performed to compare the base metal and weld metal strengths.

Ductility is another critical weld property. In addition to defects, many welding processes can produce hard, brittle microstructures. The standard measures of ductility—percent reduction in area and percent elongation—are obtained in a uniaxial tensile test. Another test often specified for welds is a bend test (face bends, root bends, and side bends). In this test, a strip of material containing a weld is deformed around a specified radius and its surface is examined. The criteria for success or failure are the number and size of defects seen on the outer surface of the bend.

Toughness is the ability of a material to absorb energy during fracture. Impact testing is the most prevalent method used to evaluate weld toughness. To test impact toughness, a sample of specified geometry is subjected to an impact load, and the amount of energy absorbed during fracture is recorded. Usually the specimen is oriented so that the notch and expected plane of fracture run longitudinally through the weld metal. Charpy tests do not measure an inherent material property, but they result in a relative measure of impact toughness between materials. A very common use of the Charpy test is to determine a material's ductile-to-brittle transition temperature by performing tests at several different temperatures.

ACKNOWLEDGMENTS

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CHAPTER 6

Solid-State Welding and Bonding

SOLID-STATE WELDING processes are those that produce coalescence of the faying surfaces at temperatures below the melting point of the base metals being joined without the addition of brazing or solder filler metal. While no pressure may be appropriate in some instances, high pressures are normally associated with diffusion bonding and welding processes. These processes use either deformation or diffusion and limited deformation to produce high-quality joints between both similar and/or dissimilar materials. Specific solid-state welding processes include:

- Diffusion welding, also commonly referred to as diffusion bonding
- Forge welding
- Roll welding
- Coextrusion welding
- Cold welding
- Friction welding
- Friction stir welding
- Explosion welding
- Ultrasonic welding

Process conditions with each of these methods may allow solid-state metallurgical reactions to occur in the weld zone. When metallurgical reactions occur, they can either benefit or adversely affect the properties of the joint. From a metallurgical perspective, the application of both fusion welding and solid-state welding processes must be evaluated using appropriate weldability testing methods for their ability to either recreate or retain base metal properties across the joint. These weldability evaluations combine material, process, and procedure aspects to identify combinations that would provide a weld joint with an acceptable set of properties.

Solid-state welding processes also have special joint design or part cross-sectional requirements. For example, continuous-drive and inertia friction welding processes require that one of the parts exhibit a circular or near-circular cross section. Diffusion bonding is another solid-state welding process that allows joining of a variety of structural materials, both metals and nonmetals. However, diffusion bonding requires a smooth surface finish to provide intimate contact of parts, a high temperature, and a high pressure: (a) to allow intimate contact of the parts along the bond interface, followed by plastic deformation of the surface asperities (on a microscopic scale), and (b) to promote diffusion across the bond interface. The need to apply pressure while maintaining part alignment imposes a severe limitation on joint design.

Alternatively, when exceptional surface finish is difficult to achieve, a metallurgically compatible, low-melting interlayer can be inserted between the parts to produce a transient liquid phase on heating. On subsequent cooling, this liquid phase undergoes progressive solidification, aided by diffusion across the solid/liquid interfaces, and thereby joins the parts. This process is called diffusion brazing and is discussed in Chapter 7.

6.1 Diffusion Bonding

Diffusion bonding is only one of many solid-state joining processes where joining is accomplished without the need for a liquid interface (brazing) or the creation of a cast product via melting and resolidification (welding). In its most narrow definition, which is used to differentiate it from other joining processes such as deformation bonding or diffusion brazing, diffusion bonding is a process that produces solid-state coalescence between two materials under the following conditions:

- Joining occurs at a temperature below the melting temperature, T_m, of the materials to be joined (usually >0.5 T_m).
- Coalescence of contacting surfaces is produced with loads below those that would cause macroscopic deformation to the part.
- A bonding aid can be used, such as an interface foil or coating, to either facilitate bonding or prevent the creation of brittle phases between dissimilar materials, but the material should not produce a low-temperature liquid eutectic reaction with the materials to be joined.

Thus, diffusion bonding facilitates the joining of materials to produce components with no abrupt discontinuity in the microstructure and with minimum deformation.

The major advantages of the diffusion bonding process are:

- It allows the preparation of stress-relieved and, in many cases, primarily homogeneous joints on very different materials.

- It allows the welding of material combinations that cannot be joined by fusion welding. This applies to materials that form brittle intermetallic phases and to metals that are joined to nonmetals.
- It enables the joining of components with very different joining surface geometries that are not subject to any particular requirements. However, the pressure application method can be a limiting factor. Materials are joined in the solid state. Metallurgical conditions are generally favorable and easy to influence, because there is less shrinkage and fewer stresses.
- Component deformation is kept within relatively close limits, thereby omitting the need for reworking in many cases.
- The process can be almost fully automated. Therefore, highly qualified technicians are not required for production tasks.

The disadvantages of diffusion bonding are:

- High equipment cost
- High demands in terms of surface cleanliness and precision, as well as bonding atmosphere
- Considerable time requirements for executing the joint, exceeding by far the requirements of most other processes
- Increased capital costs with increasing component size, because a bonding chamber becomes necessary
- Significantly impaired verification of proper joint execution by nondestructive testing in many cases

The diffusion bonding process, that is, the application of pressure and temperature to an interface for a prescribed period of time, is generally considered complete when cavities fully close at the faying surfaces. Parent metal strength is approached only for materials with surface conditions that do not have barriers to impede atomic bonding, such as surface oxides or absorbed gases at the bonding interface. In practice, oxide-free conditions exist only for a limited number of materials. Accordingly, the properties of real surfaces limit and impede the extent of diffusion bonding. The most notable exception is titanium alloys, which, at diffusion bonding temperatures >850 °C (>1560 °F), can readily dissolve minor amounts of adsorbed gases and thin surface oxide films and diffuse them away from the bonding surfaces so that they do not impede the formation of the required metallic bonds across the bond interface. Similarly, the joining of silver at 200 °C (390 °F) requires no deformation to break up and disperse oxides, because silver oxide dissociates completely at 190 °C (375 °F). Above this temperature, silver dissolves its oxide and also scavenges many surface contaminants. Other examples of metals that have a high solubility for interstitial contaminants include tantalum, tungsten, copper, iron, zirconium, and niobium. Accordingly, this class of alloys is easiest to diffusion bond.

A second class of materials, metals and alloys that exhibit very low solubility for interstitials (e.g., aluminum-, iron-, nickel-, and cobalt-based alloys), are not readily diffusion bondable. Special procedures must be used to remove surface barriers to atomic diffusion before joining and to prevent their reformation during the joining process. This is not an easy processing matter. Accordingly, the potential for high-strength bond interfaces for alloys with low interstitial solubility should be considered on an individual alloy basis.

In diffusion bonding, the nature of the joining process is essentially the coalescence of two atomically clean solid surfaces. Complete coalescence occurs through a three-stage metallurgical sequence of events. Each stage is associated with a particular metallurgical mechanism that makes the dominant contribution to the bonding process. Consequently, the stages are not discretely defined, but begin and end gradually, because the metallurgical mechanisms overlap in time. During the first stage (Fig. 6.1a), the contact area grows to a large fraction of the joint area by localized deformation of the contacting surface asperities. Surface roughness, yield strength, work hardening, temperature, and pressure are of primary importance during this stage. At the completion of this stage, the interface boundary is no longer a planar interface but consists of voids separated by areas of intimate contact. In these areas of contact, the joint becomes equivalent to a grain boundary between the grains on each surface. The first stage is usually of short duration for the common case of relatively high-pressure diffusion bonding.

During the second stage of joint formation (Fig. 6.1b), two changes occur simultaneously: all of the voids in the joint shrink, and most are eliminated; and the interfacial grain boundary migrates out of the plane of

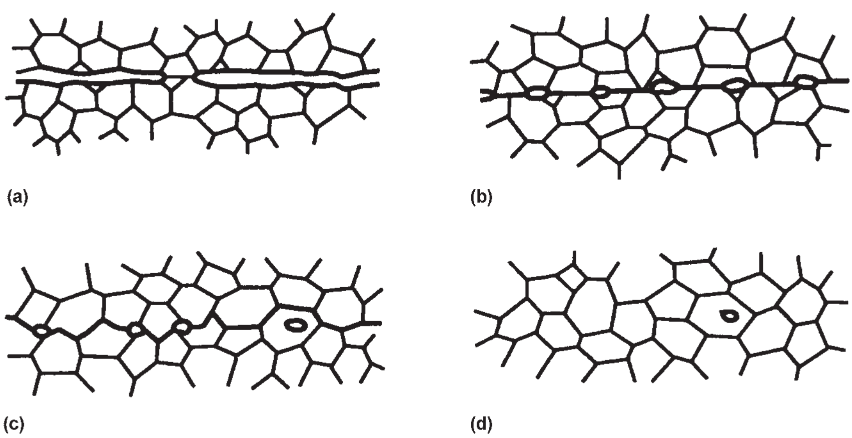


Fig. 6.1 Sequence of metallurgical stages in the diffusion bonding process. (a) Initial contact: limited to a few asperities (room temperature). (b) First stage: deformation of surface asperities by plastic flow and creep. (c) Second stage: grain-boundary diffusion of atoms to the voids and grain-boundary migration. (d) Third stage: volume diffusion of atoms to the voids. Source: Ref 6.1

the joint to a lower-energy equilibrium. Creep and diffusion mechanisms are important during the second stage of bonding, and for most, if not all, practical applications, bonding would be considered essentially complete after this stage. During the third stage of bonding (Fig. 6.1c), the interfacial grain boundary moves, and any remaining voids are engulfed within grains where they are no longer in contact with a grain boundary. The voids are very small and very likely have no impact on interface strength. Again, diffusion processes cause the shrinkage and elimination of voids, but the only possible diffusion path is now through the volume of the grains themselves.

The nature of the starting surface is of considerable importance because of the small macroscopic deformation allowed during diffusion bonding. A real surface is never perfectly clean or perfectly smooth, and the area of metal-to-metal contact between faying surfaces is a very small fraction of the area of joint contact. Contact is limited to a relatively few microasperities. At room temperature under load, these asperities deform as long as the surface area of contact is such that the yield strength of the material is exceeded. The extent of this deformation is limited at room temperature and is even more limited for work-hardenable materials. As the temperature increases to the diffusion bonding temperature, the flow stress of the material decreases and additional asperity deformation occurs through plastic flow. Again, flow occurs until the area of contact increases to an extent that the yield strength of the material is exceeded. If the temperature is above the recrystalization temperature of the material, then work hardening is no longer a consideration. With time at temperature, creep mechanisms now control the rate of asperity deformation, and the area of contact or bond continues to grow. As the area of contract grows, the stress acting on the surface asperities decreases. Consequently, creep deformation progressively slows and diminishes in significance.

The contributions of temperature and pressure to both plastic and creep deformation during this initial stage of diffusion bonding are synergistic; that is, at higher temperatures, less pressure is required and vice versa. However, for any combination of temperature and pressure, bulk deformation to the part is limited to a small percentage (<2 to 3%). Ideally, at the completion of the first stage, the extent of asperity collapse should result in a planar area of contacting surfaces with individually dispersed voids. It is necessary to achieve this extend of contact in order to complete the final stages of diffusion bonding in a reasonable period of time.

For example, Fig. 6.2 illustrates the influence of pressure on the bond line morphology for a titanium alloy. At lower pressures, where surface asperity deformation is less during the first stage of bonding, large voids remain at the interface, even after a reasonable time at temperature. Conversely, with higher applied pressure and correspondingly greater initial interface deformation, the bond interface becomes indistinguishable from the matrix alloy. Note that, by definition, very little bulk deformation is allowed and that only interface microdeformation contributes to the growth in contact area of the faying surfaces.

Mass production is not possible when the diffusion bonding process is used. The type of equipment, process temperatures, atmospheres, materials, component sizes, and numbers of workpieces can differ in each application and can result in entirely different systems and devices. The process is frequently conducted in facilities designed for other purposes, such as hot presses, hot isostatic pressing facilities, and vacuum or inert-atmosphere furnaces (with dead-weight loading). Figure 6.3 shows a typical equipment design.

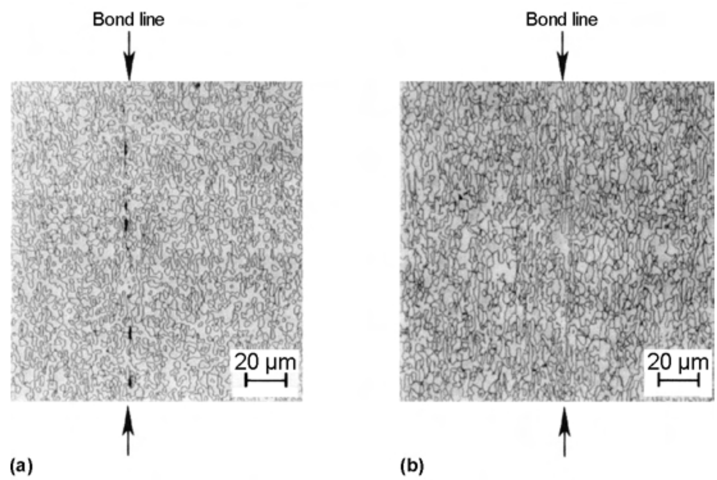


Fig. 6.2 Effect of pressure on presence of voids at bond interface of titanium alloy diffusion bonded at temperatures of 980 °C (1795 °F) for 2 h: (a) incomplete bond at 7.0 MPa (1.0 ksi), and (b) complete bond at 10.0 MPa (1.5 ksi). Source: Ref 6.2

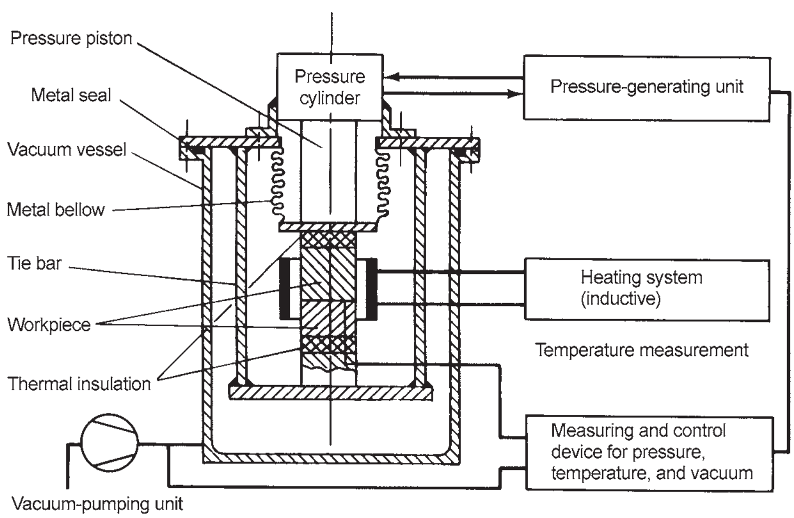


Fig. 6.3 Typical diffusion bonding equipment. Source: Ref 6.1

For titanium alloys, superplastic forming can be combined with diffusion bonding (SPF/DB) to form a one-piece unitized structure (Fig. 6.4). Titanium is very amendable to diffusion bonding because the thin protective oxide layer (TiO_2) dissolves into the titanium above 1150 °F, leaving a clean surface. Internal sheets of the multilayer preform are formed into integral stiffening members between the outer sheets, with the geometry of the stiffening core determined by the resistance welding patterns. Truss core, sinusoidal, egg-crate, and other internal stiffening geometries can be produced in a single forming step using automated welding patterns. Low forming pressures and single-step processing significantly reduce tooling costs compared with conventional methods.

6.2 Forge Welding

Forge welding is the oldest of all the welding processes, as practiced by blacksmiths since antiquity (Fig. 6.5). Forge welding is a solid-state process in which the workpieces are heated to the welding temperature and then applied with blows sufficient to cause permanent deformation at the faying surfaces. It is most commonly applied to the butt welding of steels. As contrasted with hot pressure welding of ductile face-centered cubic (fcc) metals, which is normally performed at temperatures <0.5 T_m (melting temperature), forge welding is typically conducted at temperatures in the range of 0.8 to 0.9 T_m. The forge welding temperature is generally selected to be as high as possible with due consideration to avoiding such metallurgical problems as hot shortness, embrittlement, sensitization, and excessive grain coarsening. This implies an understanding of the unique metallurgical properties of the alloy to be forged.

Forge welding requires the application of pressure by means of a hammer (hammer welding), rolls (roll welding), or dies (die welding). Joint configurations differ depending on whether the joints are to be produced manually or by using automatic equipment. Typical joint designs used in

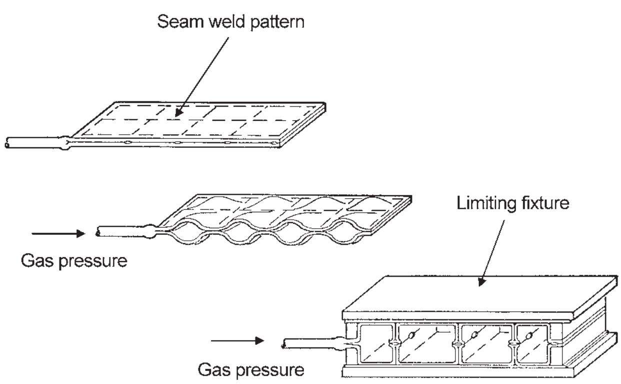


Fig. 6.4 Schematic of four-sheet superplastic forming/diffusion bonding (SPF/DB) process

manual forge welding operations are shown in Fig. 6.6. The joint surfaces in Fig. 6.6 are slightly rounded or crowned to ensure that the centerline region of the components joined will be welded first, to force any contaminants (e.g., slag, dirt, or oxide) on the surfaces out of the joint. Typical joint configurations used for automatic forge welding operations are shown in Fig. 6.7.

Hydraulic presses are typically employed to apply pressure. Presses are often highly automated, featuring microprocessor control of pressure and temperature cycles. Heat is applied locally to the joint area by multiple-tip oxyacetylene torches, resistance heating, or induction heating. Often the oxyacetylene torches are oscillated to ensure uniformity of heating. In a

Fig. 6.5 Forging is one of the oldest crafts. From this shaping of metal by heat and hammering came the idea of forcing metal together by forge welding. Source: Ref 6.3, p 2

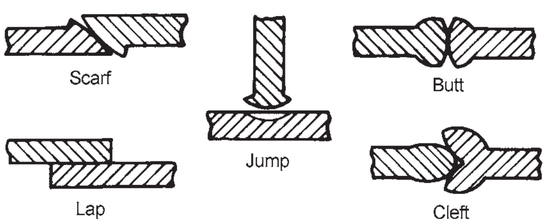


Fig. 6.6 Typical joint configurations used for manual forge welding applications. Source: Ref 6.4

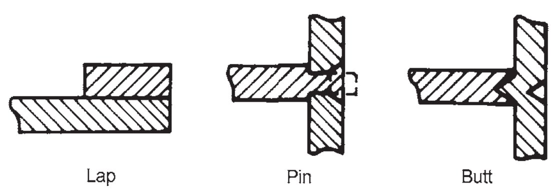


Fig. 6.7 Recommended joint configurations used in automatic forge welding applications. Source: Ref 6.4

closely related process, magnetically induced arc butt welding, the surfaces to be welded are heated by a rapidly rotating arc plasma. Generally, the process is conducted in the open air, with oxygen partially excluded from the joint area by the initial contact of the faying surfaces. When employing oxyacetylene torches, a slightly reducing flame affords some atmospheric protection. Vacuum, inert, and reducing atmospheres have also been used.

The normal welding sequence is to: (1) apply sufficient pressure to firmly seat the faying surfaces against one another, (2) heat the joint to welding temperature, and (3) rapidly apply additional pressure to upset the weld zone. Typical weld durations are 1 to 2 min. A less common procedure is to initially apply high pressure and permit deformation to occur during the heating cycle. Most forge welding employs sufficient pressure to upset the surface until the increase in the surface area is 125% or more. However, such high deformation tends to cause flow lines to bend toward the surface during upsetting. Consequently, alloys that contain significant stringers and inclusions may exhibit poor impact or fatigue properties when welded with high amounts of upset. This effect can be minimized by reducing the upset, which normally requires increasing the welding temperature and/or time to ensure complete elimination of voids and surface oxide.

Forge welding is most commonly applied to carbon and low-alloy steels, with typical welding temperatures of about 1125 °C (2060 °F). Low-carbon steels can be used in the as-welded condition, but medium-carbon steels and low-alloy steels normally are given full heat treatments after welding. In those cases where full heat treatment is impractical but hardening due to rapid cooling has occurred, induction heating may be used to temper the weld zone. Other metals welded by forge welding include high-alloy steels, nickel-based alloys, cobalt-based alloys, aluminum alloys, titanium alloys, and tungsten. Applications of this process include welding rods, bars, tubes, rails, aircraft landing gear, chains, and cans.

6.3 Roll Welding

Roll welding is a process in which two or more sheets or plates are stacked together and then passed through rolls until sufficient deformation has occurred to produce solid-state welds. Two modes of roll welding are common. In the first mode, the parts to be welded are merely stacked and passed through the rolls. The second method, usually termed *pack rolling*, involves sealing the parts to be rolled in a pack or sheath and then roll welding the pack assembly. The first method is more generally employed in the cold welding of ductile metals and alloys. Sometimes the stack to be welded is first tack welded at several locations to ensure alignment during rolling. Also, when using this method, the deformation during the first rolling pass must exceed the threshold for welding (typically >60% for cold rolling) to keep the parts together. The required first-pass reduction can be reduced by hot rolling, if the metals to be rolled can tolerate preheating without excessive oxidation. Once the first pass has been accomplished, the reduction per pass can be decreased, as is often desirable because roll-separating forces increase as the parts to be rolled become thinner. However, the nonuniform stress distribution that builds up during a sequence of very light passes can cause the weld to open up or “alligator.” Therefore, the reduction for subsequent passes is generally a compromise between applying excessive separating forces and alligatoring.

In pack roll welding, the parts to be welded are completely enclosed in a pack that is sealed (typically by fusion welding) and often evacuated to provide a vacuum atmosphere. This may be accomplished by a frame that surrounds the parts to be welded that is sandwiched by two lids or may simply consist of two covers formed to encapsulate the parts to be welded. Semikilled or killed low-carbon steel is a common material for the pack but is not suitable for all alloy and temperature combinations. Although the preparation costs of pack roll welding are significant, the process has the advantages of: (a) providing atmospheric protection, which may be particularly important for reactive alloys such as titanium, zirconium, niobium, and tantalum; and (b) permitting welding of complex assemblies involving several layers of parts. A significant limitation of the process is that packs become difficult to process when their length exceeds several feet.

An application of roll welding is the production of clad material for the minting of coins by the U.S. Mint. Rising silver prices in the 1960s and 1970s resulted in the introduction of coins made from new materials. These coins required a unique set of properties for acceptance by the general public and for use in automatic vending machines. Copper clad with copper-nickel was found to meet these requirements. Although stringent in its requirement for surface preparation, the cladding process is relatively simple (Fig. 6.8). Clad strips are produced by continuous rolling, with the surfaces prepared just before rolling by processes such as wire

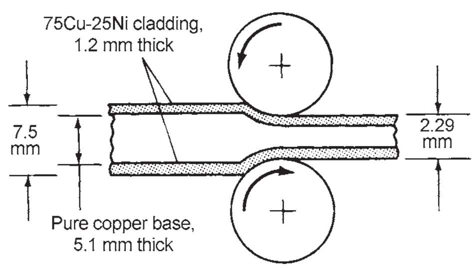


Fig. 6.8 Schematic showing 70% reduction in cross section of a U.S. Mint quarter coin (composed of an inside layer of pure copper sandwiched between two thin layers of cupronickel material) as it undergoes an initial roll welding operation. A second rolling operation further reduces the material to a final thickness of 1.36 mm (0.0535 in.) for a total reduction of 82%. Source: Ref 6.5

brushing. Welding typically is accomplished in a single rolling pass. Subsequent heat treatments may be employed to improve the weld quality by processes such as sintering, diffusion, and recrystallization. The most common metals that are roll welded are low-carbon steels, aluminum and aluminum alloys, copper and copper alloys, and nickel. Low-alloy steels, high-alloy steels, nickel-based alloys, and titanium and titanium alloys have also been roll welded.

6.4 Coextrusion Welding

Coextrusion welding is a solid-state process that produces a weld by heating two or more workpieces to the welding temperature and then forcing them through an extrusion die. The process typically is conducted at elevated temperatures, not only to improve welding but also to lower extrusion pressures. Some cold coextrusion welding of aluminum and copper has been performed. For hot coextrusion, the parts to be welded are often assembled in a can or retort that is designed with the appropriate leading taper and wall thickness to promote the initiation of extrusion. For reactive metals, such as zirconium, titanium, and tantalum, the retort may be evacuated and sealed. Both forward and back coextrusion have been employed, but forward coextrusion is the usual mode. A principal advantage of coextrusion welding is that the high isostatic pressures associated with the process are favorable to the deformation welding of low-ductility alloys.

In a similar process, extrusion welding has been used to butt weld tubes. The ends of the tubes are prepared for extrusion by beveling at a 45 to 60° angle to produce an overlapping joint (Fig. 6.9). The leading tube contains the female portion of the beveled joint and is the stronger of the two metals in dissimilar metal joints. Extrusion press die angles of 30 to 35° are common. An advantage of extrusion welding over other methods of deformation butt welding of tubes is that there is no flash or upset to remove after extrusion.

The most common metals welded by the coextrusion process include low-carbon steel, aluminum, aluminum alloys, copper, and copper alloys.

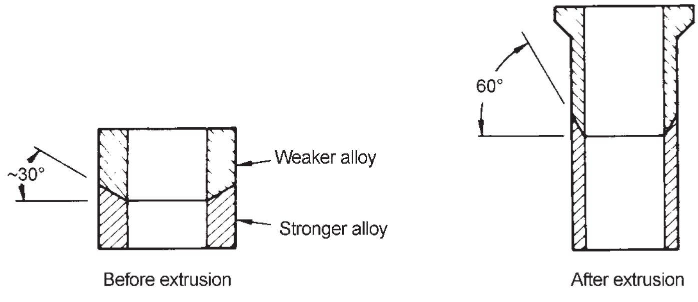


Fig. 6.9 Design for butt welding of tube by coextrusion. Source: Ref 6.6

Additional applicable materials include nickel, nickel-based alloys, zirconium, titanium, tantalum, and niobium.

6.5 Cold Welding

Cold welding (also known as cold-pressure welding) in normal ambient conditions involves the destruction of the surface oxide layers of the metallic materials in the weld area. This exposes areas of clean metal surface on the two components to be welded, which must be brought into contact with each other to generate the interatomic forces needed to form a weld. The technique is frequently used with nonferrous metals, primarily copper and aluminum. A chart showing the combinations of metals that can be successfully cold welded is shown in Fig. 6.10. Because welding lends itself to numerous techniques of forming, there are many variants of the cold pressure welding process. In order to obtain bonding in cold welding, plastic deformation of one or both metals is required, implying that a basic parameter is the degree of deformation. This is normally expressed as the surface expansion, X, or the degree of surface exposure, Y:

$$X = \frac{A_1 - A_0}{A_0} \qquad Y = \frac{A_1 - A_0}{A_1}$$

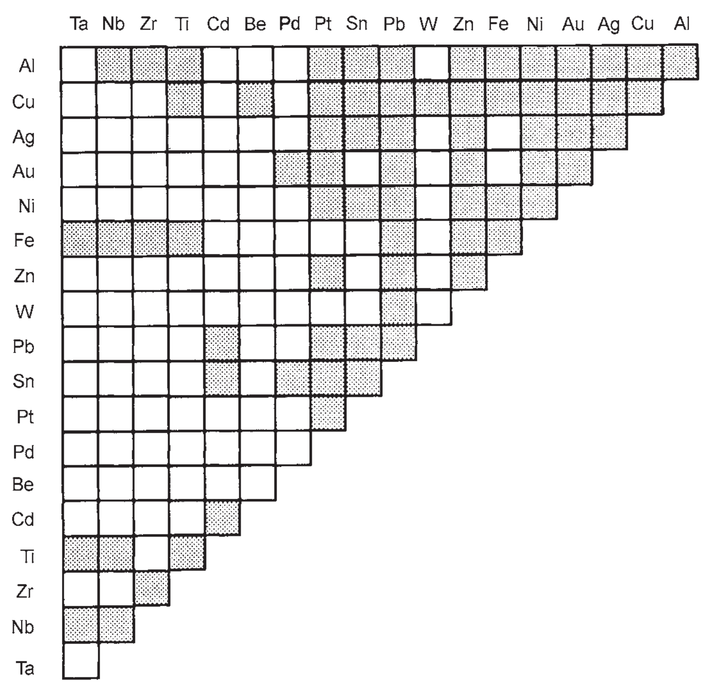


Fig. 6.10 Chart showing combinations of metals that can be successfully cold welded (indicated by shaded boxes). Source: Ref 6.7

where A_0 is the initial and A_1 is the final interface area. Figure 6.11 shows the shear bond strength, τ_B, obtained in roll bonding of sheets in various combinations, plotted as a function of Y, which equals the thickness reduction in rolling:

$$Y = r = \frac{t_0 - t_1}{t_0}$$

A threshold surface exposure has to be reached before bonding occurs. Beyond this threshold, which depends on the metal combination, the bond strength increases rapidly, with Y reaching a level corresponding to the strength of the weaker metal. This relationship between bond strength and surface exposure is fundamental to all cold welding processes, but the threshold surface expansion for a given metal combination depends on the type of forming process applied for cold welding.

Surface preparation before cold welding is of utmost importance. In most welding applications, surface preparation consists of degreasing followed by scratch brushing. This produces a hard, brittle surface layer, which will crack when subjected to expansion. At larger surface expansions, virgin material is exposed, which extrudes through the cracks of the surface layer and meets similarly exposed surface area from the opposing metal. Although scratch brushing is normally applied as the method of surface preparation, it has certain disadvantages. The bond strength obtained is variable with rather large scatter caused by the rough surface treatment. Cold welding has to be carried out as soon as possible after scratch brushing and within 10 min. Systematic investigations of cold roll bonding of aluminum-aluminum, aluminum-copper, copper-copper, and aluminum-mild steel, applying different methods of dressing the workpiece surfaces before cold welding, show that electrochemical and chemical plating are good alternatives to scratch brushing. The optimum choice

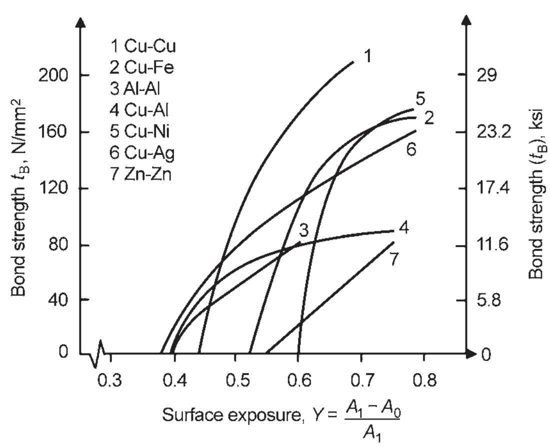


Fig. 6.11 Bond shear strength versus surface exposure/reduction in cold roll bonding. Source: Ref 6.8

of surface preparation depends on the metal combination. Electroless nickel plating is optimum for copper-copper and aluminum-aluminum, whereas scratch brushing is the most efficient in case of cold roll bonding of aluminum-copper and aluminum-mild steel.

A variety of metal forming processes are suitable for production of cold welds. The following processes are most commonly applied in industry:

Rolling. After the sheets are cleaned, they are roll bonded together, reducing thickness to approximately 20%. The roll bonding may be carried out at elevated temperature to facilitate deformation in case of harder metal combinations. Subsequent heat treatment may be applied to improve bond strength by diffusion.

Indentation. Lap joining by local indentation in the two plates or bars to be welded is a common cold welding operation, normally carried out by small tool indentation. Indentation may be done from both sides with opposing indentors (Fig. 6.12a) or from one side only, using an indentor tool and a flat anvil (Fig. 6.12b). The indentors may be of round or rectangular cross section, with a diameter or minimum cross section typically being one to three times the thickness of the sheets. The required thickness reduction is 50 to 90%. The indentors are usually provided with a shoulder that controls the amount of deformation, minimizes distortion, and promotes welding in the peripheral area surrounding the indentor. In welding dissimilar metals it is often necessary to increase the size of the indentor or to employ a flat anvil on the softer metal side. Lap joining is typically

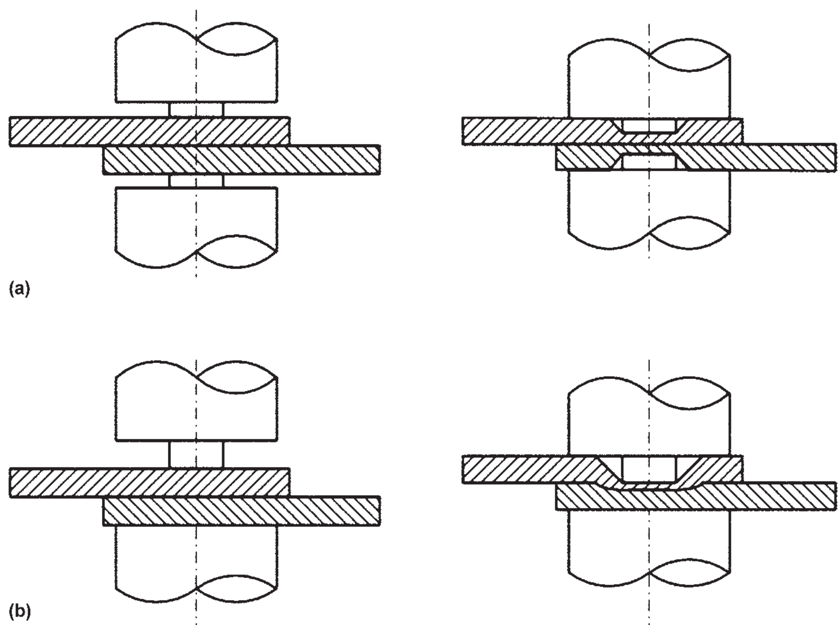
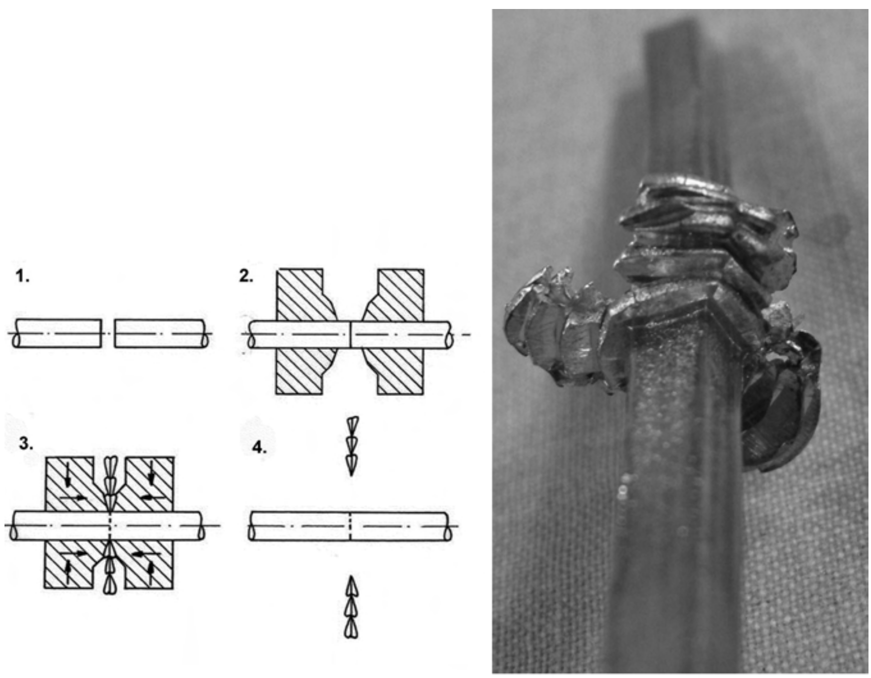


Fig. 6.12 Lap joining by (a) double-sided tool indentation and (b) single-sided tool indentation. Source: Ref 6.8

applied to join aluminum-aluminum, aluminum-copper, and copper-copper, including alloys for electricity supply.

Butt Welding. Cold butt welding of wires, bars, or plates end to end is performed by securing the two workpieces in special clamps in such a way that a free length of each workpiece protrudes from the clamps (Fig. 6.13). The free ends are pressed together, and the axial upset results in plastic deformation of the projecting ends moving the original, contaminated end surfaces into the flash and forming a strong bond between virgin surfaces in the welding region. To obtain a good bond, multiple upsetting is performed two to six times. When welding aluminum-aluminum, aluminum-copper, and copper-copper, the weld strength is greater than the base metal strength and there is no increase of electrical resistance in the welds.

Extrusion. Tube transition joints of aluminum-stainless steel, aluminum-titanium, and zirconium-mild steel are manufactured for nuclear power and space technology by forward tube extrusion. The harder tube is placed nearest to the conical die opening (Fig. 6.14a). The punch is provided with a mandrel fitting the tube holes, thereby eliminating inward flow. Electronic devices and nuclear fuel elements are encapsulated by cold welding using an extrusion process, where the lid is joined to the can housing by an ironing operation (Fig. 6.14b).



(a) (b)

Fig. 6.13 (a) Schematic outline of cold butt welding with multiple upset, and (b) cold butt welded copper bar, cross section 3 × 5 mm. Source: Ref 6.8

Shear Welding. In several special cases, use of relative sliding between two surfaces in the so-called shear welding has found application. Figure 6.15(a) to (c) shows the principle of combining extruded aluminum profiles using a “groove and tongue”-like joint. The groove geometry ensures large local surface expansion, and the taper of the tongue ensures high normal pressure in the interface, which, together with the shear deformation, establish the conditions necessary for cold welding. This technique is

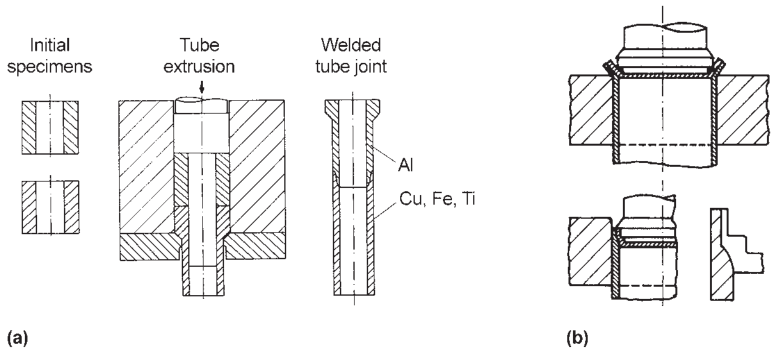


Fig. 6.14 (a) Forward tube extrusion of transition joints, and (b) encapsulation by ironing. Source: Ref 6.8

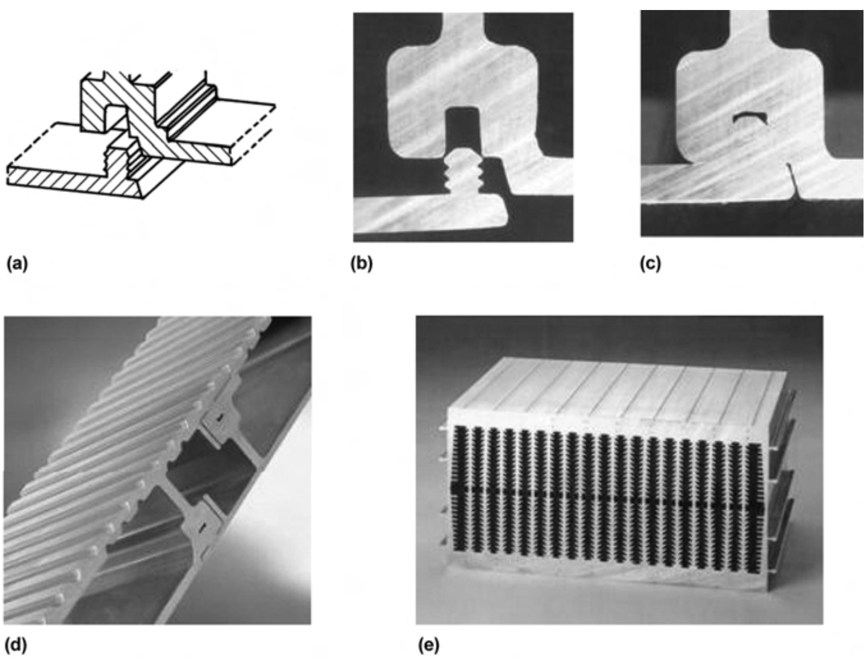


Fig. 6.15 Shear welding: (a) and (b) extruded groove and tongue for shear welding, (c) assembled joint, (d) sandwich constructions assembled by shear welding of extruded aluminum profiles, and (e) air cooler. Source: Ref 6.8

applied for joining half-open aluminum extrusion profiles to closed sandwich constructions (Fig. 6.15d). They are used for house building, stiffened panels for containers, trucks, and vans, and ships sides. Figure 6.15e shows an air cooler assembled by the same technique.

6.6 Friction Welding

Friction welding is a process in which the heat for welding is produced by direct conversion of mechanical energy to thermal energy at the interface of the workpieces without the application of electrical energy or heat from other sources. Friction welds are made by holding a nonrotating workpiece in contact with a rotating workpiece under constant or gradually increasing pressure until the interface reaches welding temperature and then stopping rotation to complete the weld (Fig. 6.16). The rotational speed, axial pressure, and welding time are the principal variables that are controlled in order to provide the necessary combination of heat and pressure to form the weldment. These parameters are adjusted so that the interface is heated into the plastic temperature range where welding can take place. Once the interface is heated, axial pressure is used to bring the weld interfaces into intimate contact. During this last stage of the welding process, atomic diffusion occurs while the interfaces are in contact, allowing a metallurgical bond to form between the two materials. If incipient melting does occur, there is no evidence in the finished weld because the metal is worked during the welding stage.

There are two principal friction welding methods: direct-drive welding and inertia-drive welding. Direct-drive friction welding, sometimes called conventional friction welding, uses a motor running at constant speed to input energy to the weld. Inertia-drive friction welding, sometimes called flywheel friction welding, uses the energy stored in a flywheel to input energy to the weld. The major difference between the direct-drive and inertia-drive methods is the speed during the friction stage: in inertia-drive welding the speed continuously decreases during the friction stage, whereas in direct-drive welding the speed remains constant. End preparation of workpieces, other than that necessary to ensure reasonably good axial alignment and to produce the required length tolerance for a specific set of welding conditions, is not critical. Frictional wear removes irregu-

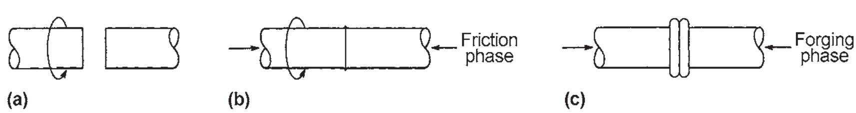


Fig. 6.16 Fundamental steps in the friction welding process: (a) one workpiece is rotated, and the other workpiece is held stationary; (b) both workpieces are brought together, and an axial force is applied to begin the upsetting process; (c) workpiece rotation is stopped, and the upsetting process is completed. Source: Ref 6.9

larities from the joint surfaces and leaves clean, smooth surfaces that are then heated to welding temperature.

In friction welding, the joint face of at least one of the workpieces must be essentially round. The rotating workpiece should be somewhat concentric in shape because it revolves at a relatively high speed. Workpieces that are not round, such as hexagon-shape workpieces, have been friction welded successfully, but the resulting weld upset is rough, asymmetrical, and difficult to remove without damaging the welded assembly. For special applications, welding machines have been modified so that the spindle stops at the same place each time, thus making it possible for workpieces to be oriented to each other.

Many ferrous and nonferrous alloys can be friction welded. Friction welding also can be used to join metals of widely differing thermal and mechanical properties. Often combinations that can be friction welded cannot be joined by other welding processes because of the formation of brittle phases that would make such joints unserviceable. The submelting temperatures and short weld times of friction welding allow many combinations of work metals to be joined.

6.7 Friction Stir Welding

A new welding process that has the potential to revolutionize aluminum joining has been developed by The Welding Institute (Cambridge, UK). Friction stir welding is a solid-state process that operates by generating frictional heat between a rotating tool and the workpiece (Fig. 6.17). The welds are created by the combined action of frictional heating and plastic deformation due to the rotating tool. A tool with a knurled probe of hardened steel or carbide is plunged into the workpiece creating frictional heating that heats a cylindrical column of metal around the probe as well as a small region of metal underneath the probe. A number of different tool geometries have been developed, which can significantly affect the quality of the weld joint. The threads on the probe (Fig. 6.18) cause a downward component to the material flow, inducing a counterflow extrusion toward the top of the weld, or an essentially circumferential flow around the probe.

The rotation of the probe tool stirs the material into a plastic state, creating a very fine-grain microstructural bond. The tool contains a larger diameter shoulder above the knurled probe, which controls the depth of the probe and creates additional frictional heating on the top surface of the workpiece. It also prevents the highly plasticized metal from being expelled from the joint. Before welding, the workpieces have to be rigidly fixed with the edges butted to each other and must have a backing plate to withstand the downward forces exerted by the tool. A typical welding operation is shown in Fig. 6.19.

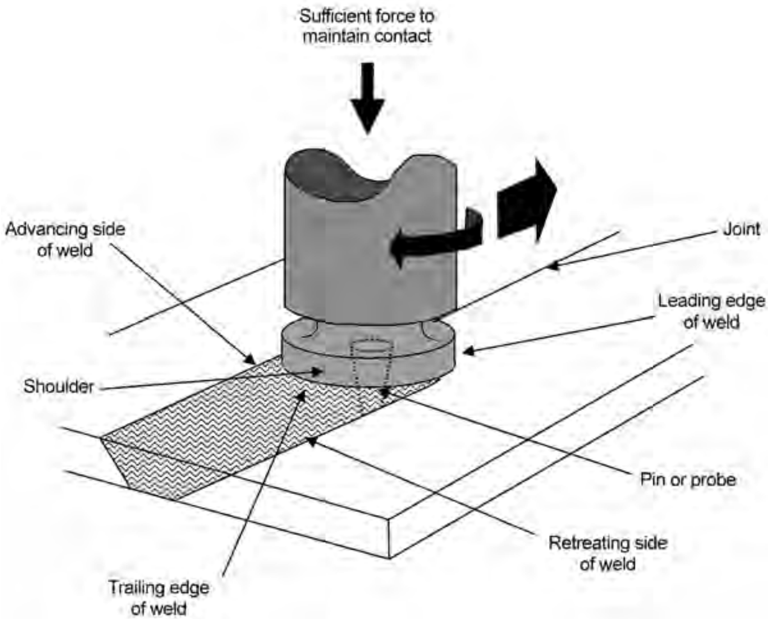


Fig. 6.17 Friction stir welding process. Source: Ref 6.10

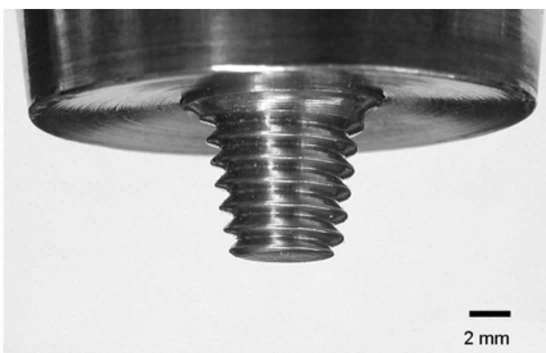


Fig. 6.18 Example of friction stir welding pin tool. Source: Ref 6.10, p 17

The larger the diameter of the shoulder, the greater the frictional heat it can contribute to the process. Once the shoulder makes contact, the thermally softened metal forms a frustum shape corresponding to the tool geometry, with the top portion next to the shoulder being wider and then tapering down to the probe diameter. The maximum temperature reached is of the order of 0.8 T_m(melting temperature). Material flows around the tool and fuses behind it. As the tool rotates, there is some inherent eccentricity in the rotation that allows the hydromechanically incompressible plasticized material to flow more easily around the probe. Heat transfer

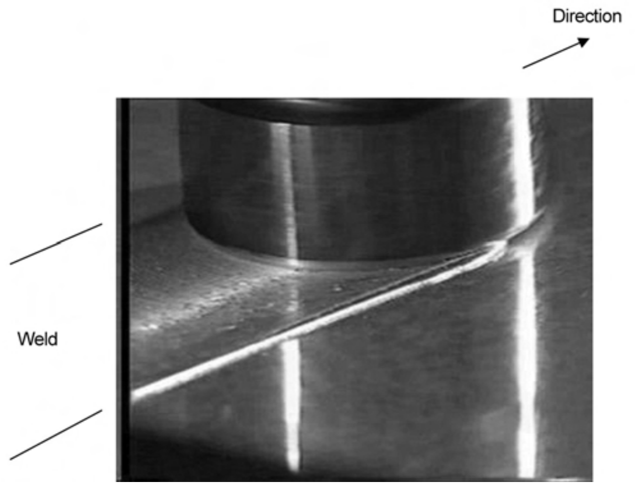


Fig. 6.19 Friction stir welding of aluminum alloy. Courtesy of ESAB Welding Equipment AB

studies have shown that only about 5% of the heat generated in friction stir welding flows into the tool, with the rest flowing into the workpieces; therefore, the heat efficiency in friction stir welding is very high relative to traditional fusion welding processes, where the heat efficiency is only about 60 to 80%.

Once the tool has penetrated the workpieces, the frictional heat caused by the rotating tool and rubbing shoulder results in frictional heating and plasticization of the surrounding material. Initially the material is extruded at the surface, but as the tool shoulder contacts the workpieces, the plasticized metal is compressed between the shoulder, workpieces, and backing plate. As the tool moves down the joint, the material is heated and plasticized at the leading edge of the tool and transported to the trailing edge of the probe, where it solidifies to form the joint.

The advantages of friction stir welding include:

- The ability to weld butt, lap, and T-joints
- Minimal or no joint preparation
- The ability to weld 2*xxx* and 7*xxx* alloys, which are difficult to fusion weld
- The ability to join dissimilar alloys
- The elimination of cracking in the fusion and heat-affected zone (HAZ)
- Lack of weld porosity
- Lack of required filler metals
- In the case of aluminum, no requirement for shielding gases.

In general, the mechanical properties are better than for many other welding processes. For example, the static properties of 2024-T351 aluminum alloy are between 80 and 90% of the parent metal, and the fatigue properties approach those of the parent metal. In a study of lap shear joints, friction stir-welded joints were 60% stronger than comparable riveted or resistance spot-welded joints.

The stir-welded joint does not demonstrate many of the defects encountered in normal fusion welding, and the distortion is significantly less. A typical weld joint (Fig. 6.20) contains a well-defined nugget with flow contours that are almost spherical in shape but are somewhat dependent on tool geometry. The Welding Institute has recommended that the microstructural classification shown in Fig. 6.20 be used for friction stir welds. The fine-grained recrystallized weld nugget and the adjacent unrecrystallized but plasticized material together are referred to as the thermomechanically affected zone (TMAZ); therefore, the TMAZ results from both thermal exposure and plastic deformation and extends from the width of the shoulder at the top surface to a narrower region on the backside. A series of concentric rings, called onion rings, are frequently observed within the weld nugget, possibly as a result of the swirling motion of the plasticized material behind the advancing tool probe. The unrecrystallized portion of the TMAZ, which has also undergone thermal exposure and plastic deformation, has a grain size similar to that of the parent metal. The HAZ is typically trapezoidal in shape for a single-pass weld, with a greater width at the tool shoulder due to the heat generated between the shoulder and the top of the workpieces. The HAZ results primarily from thermal exposure, with little or no plastic deformation present.

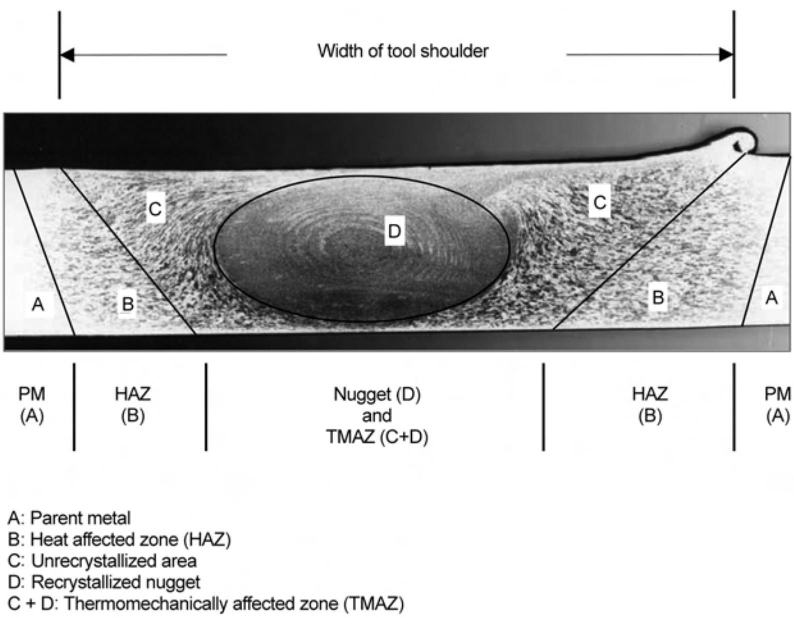


Fig. 6.20 Friction stir fusion weld. A, parent metal; B, heat-affected zone (HAZ); C, unrecrystallized area; D, recrystallized nugget; C + D, thermomechanically affected zone (TMAZ). Courtesy of The Welding Institute

The friction stir welding process has already been adapted to a number of industrial applications. In 1999, the fuel tanks on the Boeing Delta II rocket were launched with friction stir longitudinal welds. Based on this early success, Boeing purchased a large friction stir welding device to weld Delta IV fuel tanks. In addition, Lockheed Martin and NASA Marshall Space Flight Center have developed and implemented friction stir welding on the longitudinal welds of the 2195 Al-Li liquid hydrogen and liquid oxygen barrel segments of the external tank for the Space Shuttle (Fig. 6.21). Another early adopter of friction stir welding has been the marine industry for welding ship skins. Construction of high-speed trains is another important potential application for friction stir welding. Extensive research is being conducted to extend friction stir welding to other metals and their alloys.

6.8 Explosion Welding

Explosion welding, which is also referred to as explosion bonding, is a solid-state metal-joining process that uses explosive force to create an electron-sharing metallurgical bond between two metal components. Although the explosive detonation generates considerable heat, there is no time for heat transfer to the component metals; therefore, there is no appreciable temperature increase in the metals.

Explosion bonding is a cold pressure welding process in which the contaminant surface films are plastically jetted off the base metals as a result of the high-pressure collision of the two metals (Fig. 6.22). A layer of explosive is placed in contact with one surface of the prime metal plate, which is maintained at a constant parallel separation from the backer or base plate. The explosive is detonated at a point or line, and as the detonation front moves across the plate, the prime metal is deflected and accelerated to plate velocity, thus establishing an angle between the two plates. During the high-velocity collision of metal plates, a jet is formed between

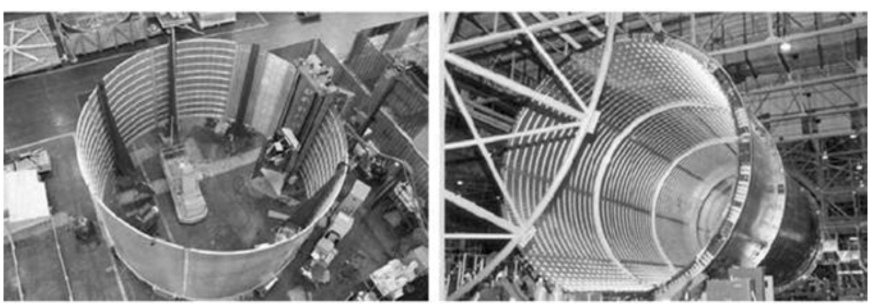


Fig. 6.21 Friction stir weld process development tool at the Marshall Space Flight Center shown with an 8.2 m (27 ft) diameter barrel segment of the 2195 Al-Li external tank for the Space Shuttle at the National Aeronautics and Space Administration (NASA) Michoud Assembly Facility in New Orleans. Courtesy of NASA's Marshall Space Flight Center. Source: Ref 6.10, p 298

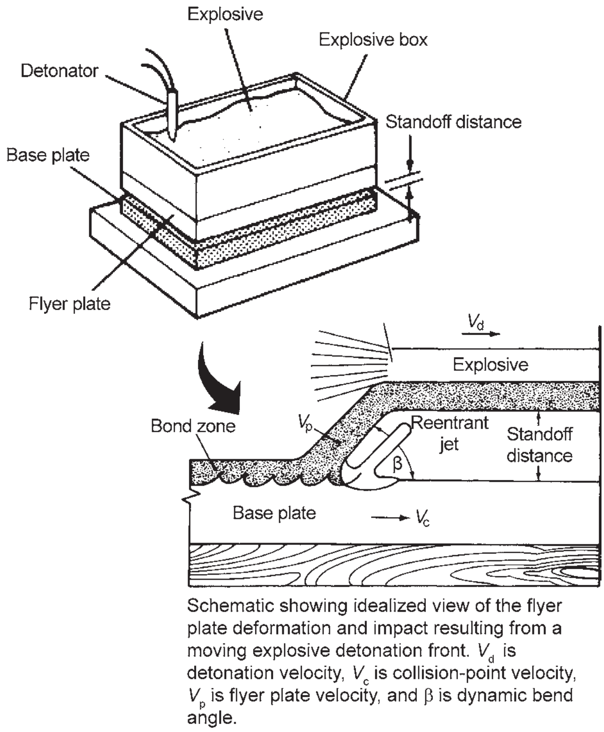


Fig. 6.22 Schematic showing key components used in parallel gap explosion welding process. Source: Ref 6.11

the metal plates if the collision angle and the collision velocity are in the range required for bonding. Contaminant surface films that are detrimental to the establishment of a metallurgical bond are swept away in the jet. The metal plates, cleaned of any surface films by the jet action, are joined at an internal point under the influence of the extremely high pressure that is obtained near the collision point.

Explosion welded metals that are commercially manufactured exhibit a wavy bond zone interface (Fig. 6.23). Aside from its technological importance, the wavy bond is remarkable because of its very regular pattern. Bond zone wave formation is analogous to fluid flowing around an obstacle. When the fluid velocity is low, the fluid flows smoothly around the obstacle; above a certain fluid velocity, the flow pattern becomes turbulent. The obstacle in explosion bonding is the point of highest pressure in the collision region. Because the pressures in this region are many times higher than the dynamic yield strength of the metals, they flow plastically in a manner similar to fluids. The microstructure of the metals at the bond zone shows clearly that the metals did not melt but flowed plastically during the process. Electron microprobe analysis across such plastically deformed areas shows that no diffusion occurs because of extremely rapid self-quenching of the metals.

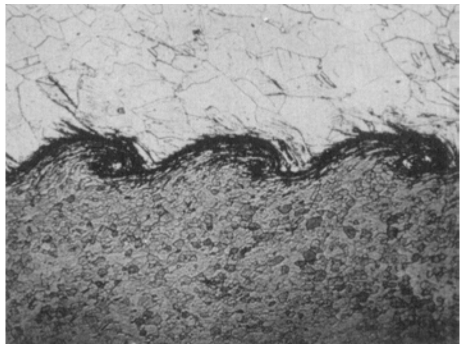


Fig. 6.23 Bond zone pattern typical of explosion clad metals. Materials are type 304L stainless steel and medium-carbon steel. 20×. Source: Ref 6.1

Explosion welding is suitable for joining metals of the same type, such as steel to steel, as well as metals with substantially different densities, melting points, and/or yield strengths, such as tantalum to a titanium alloy. The process is commonly used to join corrosion-resistant alloys to carbon or alloy steels. The only metallurgical limitation is sufficient ductility and fracture toughness to undergo the rapid deformation of the process without fracture. Generally accepted limits are 10% and 30 J (22 ft·lbf) minimum, respectively.

6.9 Ultrasonic Welding

Ultrasonic welding is used effectively for joining both similar and dissimilar metals with lap joint welds. High-frequency vibrations, introduced into the areas to be joined, disrupt the metal atoms at the interface of the weld components and produce an interlocking of these atoms to achieve a mechanical joint. No significant heating is involved; the maximum temperature at the weld interface is usually in the range of 0.35 to 0.50 T_m (absolute). The base metal does not melt and subsequently solidify with a brittle cast structure, as with high-temperature joining processes. Moderate pressure is applied during joining to maintain intimate contact between the parts, but the pressure does not cause significant deformation in the weld zone—seldom more than about 10%. Preweld cleaning requirements are minimal, while postweld cleaning and heat treatment are not necessary. Fluxes or filler metals also are not used.

Ultrasonic energy is produced through a transducer, which converts high-frequency electrical vibrations to mechanical vibrations at the same frequency, usually >15 kHz (above the audible range). Mechanical vibrations are transmitted through a coupling system to the welding tip and into the workpieces. The tip vibrates laterally, essentially parallel to the weld interface, while static force is applied perpendicular to the interface. Spot welding (Fig. 6.24) and continuous seam welding can be accomplished by this method. In spot welding, the duration of the ultrasonic pulse (usually $\leq$1 s) is selected according to the thickness and hardness of the materials being joined. For seam welding, the tip is a roller disk that rotates across the parts to be joined.

Most industrial metals can be joined to themselves or to other metals by ultrasonic welding. Ductile metals, aluminum and copper alloys, and precious metals (gold, silver, platinum, and palladium) are among the easiest to weld. Both aluminum alloys and precious metals can be joined to semiconductor materials such as germanium and silicon. Various types of iron and steel are somewhat more difficult to join. The most troublesome are refractory metals and some of the higher-strength metals, including titanium, nickel, and zirconium, and their alloys, which should be welded only in thin gages.

ACKNOWLEDGMENTS

Sections of this chapter were adapted from "Solid-State Welding Processes" in *Metals Handbook Desk Edition,* 2nd ed., ASM International, 1998. The section on cold welding was adapted from "Cold Welding" by N. Bay in *Welding Fundamentals and Processes,* Vol 6A, ASM International, 2011.

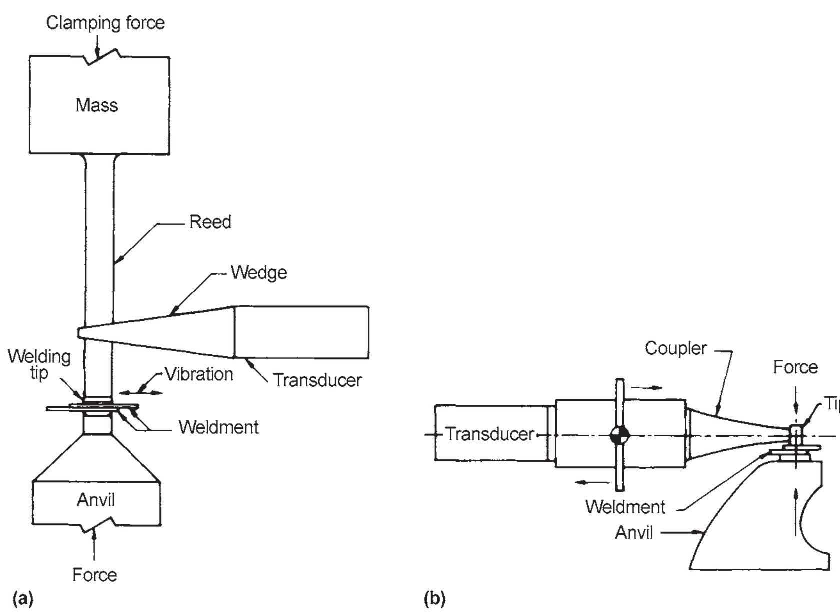


Fig. 6.24 Two versions of ultrasonic welding systems used for spot welding applications: (a) wedge-reed system and (b) lateral drive system. Source: Ref 6.12

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CHAPTER 7

Brazing and Soldering

BRAZING AND SOLDERING processes use a molten filler metal to wet the mating surfaces of a joint, with or without the aid of a fluxing agent, leading to the formation of a metallurgical bond between the filler and the respective components. Solders usually react to form intermetallic phases, that is, compounds of the constituent elements that have different atomic arrangements from the elements in solid form. By contrast, most brazes form solid solutions, which are mixtures of the constituents on an atomic scale. Joining processes of this type are defined as soldering if the filler melts at a temperature <450 °C (<840 °F) and as brazing if it melts above this temperature.

Characteristic features of soldering and brazing include:

- All brazing operations and most soldering operations involve heating the filler and joint surfaces above ambient temperature.
- In most cases, the service temperature of the assembly must be lower than the melting temperature of the filler metal.
- Even though fluxes are available that can remove most oxides and organic films, careful cleaning of the surfaces to be brazed or soldered is critical to making sound joints. In addition, fluxes leave residues that are often corrosive and can be difficult to remove.
- The appropriate joint and component geometries are governed by the filler/component material combination and by service requirements (need for hermeticity, stress loading, and positional tolerances). Complex geometries and combinations of thick and thin sections can usually be soldered or brazed together.
- Intricate assemblies can be produced with low distortion, high fatigue resistance, and good resistance to thermal shock.
- Joints tend to be strong if well filled, unless embrittling phases are produced by reaction between the filler metal and the components.

- Soldered and brazed joints can attain physical and chemical properties that approximately match and, in some cases, even exceed those of the components, but they usually have limited elevated temperature service and stability.
- Fillets are formed under favorable conditions. These can act as stress reducers at the edges of joints that benefit the overall mechanical properties of the joined assembly.
- Soldering and brazing can be applied to a wide variety of materials, including metals, ceramics, plastics, and composite materials. For many materials, and plastics in particular, it is necessary to apply a surface metallization before joining.

Advantages of brazing and soldering include:

- The joint forms itself by the nature of the flow, wetting, and subsequent crystallization process, even when the heat and the braze or solder are not directed precisely to the places to be joined.
- The process temperature is relatively low, so there is no need for the heat to be applied locally, as in welding.
- Brazing and soldering allow considerable freedom in the dimensioning of joints, so it is possible to obtain good results even if a variety of components are used on the same product.
- The brazed or soldered connections can be disconnected if necessary, thus facilitating repair.
- The equipment for both manual and machine brazing/soldering is relatively simple.
- The processes can be easily automated, offering the possibility of inline arrangements of brazing/soldering machines with other equipment.

Disadvantages of brazing and soldering include:

- Size limitation of the parts to be brazed is of major importance. Since the outer area to be brazed must be heated, large cast sections or large heavy plates cannot be easily brought up to temperature. Although very large assemblies may be brazed, welding may be more economical.
- Brazing requires tightly mating parts to ensure capillary flow of the filler metal. This often involves expensive machining to attain the desired fit.
- If not properly removed, braze and solder flux residues can cause corrosion.
- A certain degree of skill is required to perform manual brazing operations; personnel limitations may rule out the process.
- Brazing fluxes and filler rods may evolve toxic fumes and poisonous vapors. Many types of solder contain lead, which is a poison. Many

industries are attempting to move to lead-free solder, but the process is long and costly.

- Although soldered connections can be disconnected, removing the solder sometimes causes irreparable physical or electrical damage. Small wires with thin insulation can melt or burn off easily, and printed circuit boards can stand only so much heat before the circuit traces either lift off or burn.

7.1 Fundamentals of Brazing

Capillary flow is the dominant physical force that ensures good brazements when both faying surfaces to be joined are wetted by the molten filter metal. The joint must have the proper gap to permit efficient capillary action and coalescence. More specifically, capillary flow is a result of the relative attraction of the molecules of the liquid to each other and to those of the solid surface. In actual practice, brazing filler metal flow characteristics are also influenced by dynamic considerations such as fluidity, viscosity, vapor pressure, and gravity and, especially, by the effects of any metallurgical reactions between the filler metal and the base metal.

In a properly designed joint, the molten brazing filler metal is drawn completely through the joint area when processed in a protective atmosphere (Fig. 7.1). Capillary attraction is the physical force that governs the action of a liquid against solid surfaces in small, confined areas. The phenomena of wetting and spreading are very important to the formation of brazed joints. Other significant factors that also must be considered include the presence of oxide films and their effects on wetting and spreading, surface roughness, alloying between the brazing filler metal and base metal, and the extent to which alloying is affected by the thermodynamic properties of the brazing atmosphere.

Wetting is, perhaps, best explained by the following example. If a solid is immersed in a liquid bath and wetting occurs, then a thin continuous layer of liquid adheres to the solid when it is removed from the liquid (Fig. 7.2). Technically, the force of adhesion between the solid and liquid dur-

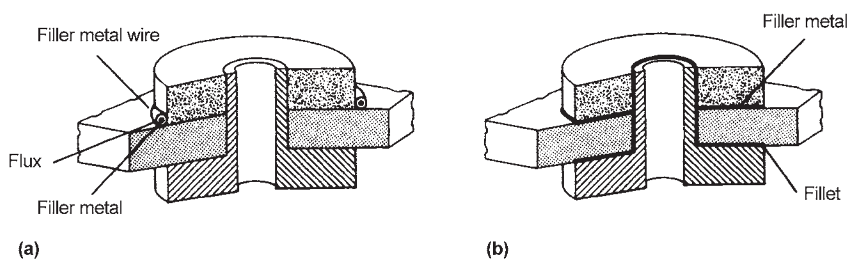

Fig. 7.1 Extensive flow capability of braze filler metal: (a) filler metal wire is placed around outer surface; (b) after brazing, filler metal has melted and flowed to close and seal all gaps. Source: Ref 7.1

ing the wetting process is greater than the cohesive force of the liquid. In practical terms, wetting implies that the liquid brazing filler metal spreads on the solid base metal instead of balling up on its surface. Wetting actually depends on a slight surface alloying of the base metal with the brazing filler metal. Lead, for example, does not alloy with iron and will not wet it. Tin, on the other hand, does form an alloy with iron, so a tin-lead solder will wet steel.

Experiments have shown that liquids placed on solid surfaces usually do not completely wet but, rather, remain as a drop that has a definite contact angle between the liquid and solid phases (Fig. 7.3). The boundary

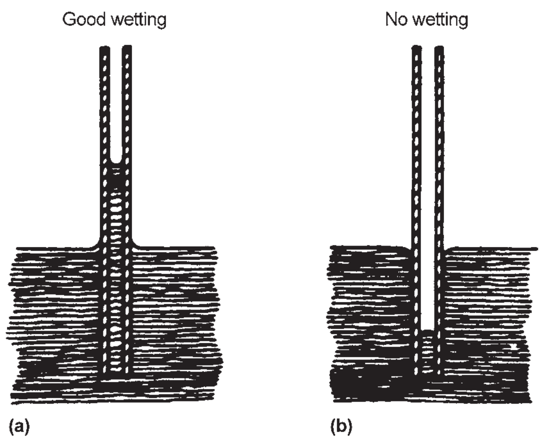

Fig. 7.2 Principle of capillary attraction for selected liquids sandwiched between two clean glass plates: (a) when immersed in water or ink, a column will rise between the plates because of wetting; (b) when the plates are immersed in mercury, no wetting occurs and the column is depressed. If paraffin plates are used instead of glass plates, immersion of the plates in mercury will produce wetting. Source: Ref 7.2

$$\cos\theta = \frac{\gamma_{SV} - \gamma_{SL}}{\gamma_{LV}}$$

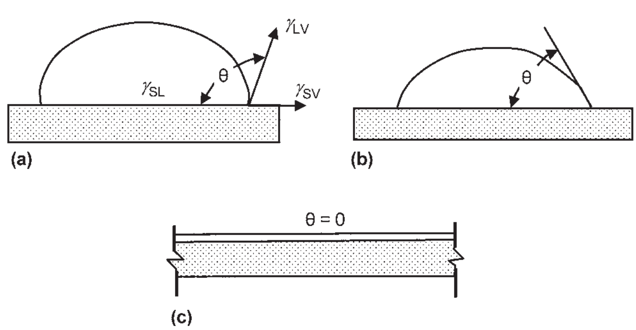

Fig. 7.3 Contact angle θ for a liquid droplet on a solid surface: (a) $\theta > 90°$, (b) $\theta < 90°$, and (c) $\theta = 0°$. γ_{SL} is the solid-liquid surface energy, γ_{SV} is the solid-vapor surface energy, and γ_{LV} is the liquid-vapor surface energy. Source: Ref 7.3, p 4

between wetting and nonwetting conditions is generally taken as $\theta = 90°$. For $\theta < 90°$, wetting occurs, while $\theta > 90°$ represents a condition of nonwetting. Spreading may be defined as the condition where the liquid completely covers the solid surfaces. This condition occurs when θ approaches the value of 0°. For most brazing systems the optimum value of θ is in the range of 10–45° and is determined by joint gap or thickness.

Another factor that affects wetting is the cleanliness of the surface to be wetted. Oxide layers inhibit wetting and spreading, as do grease, dirt, and other contaminants that prevent good contact between the brazing filler metal and the base metal. One of the functions of a flux is to dissolve the oxide layer on the joint area and thereby expose clean base metal.

It can be concluded that wetting is the ability of the molten brazing filler metal to adhere to the surface of a metal in the solid state and, when cooled below its solidus temperature, to make a strong bond with that metal. Wetting is a function not only of the nature of the brazing filler metal, but of the degree of interaction between materials to be joined. There is considerable evidence that in order to wet well, a molten metal must be capable of dissolving, or alloying with, some of the metal on which it flows.

The successful joining of components by the brazing process depends on the selected brazing filler metal having a melting temperature >450 °C (>840 °F) that wets the base metal without melting it. In addition, the joint must be designed to ensure that the mating surfaces of the components are parallel and close enough together to allow capillary flow.

7.2 Elements of the Brazing Process

Reliability and cost must be considered when designing a braze joint. Joint strength, fatigue resistance, corrosion susceptibility, and high-temperature stability are additional concerns that determine the selection of joint design, braze filler materials, and processing parameters. A careful and intelligent appraisal of the following elements is required in order to produce satisfactory brazed joints:

- Filler metal flow
- Base metal characteristics
- Filler metal characteristics
- Surface preparation
- Joint design and clearance
- Temperature and time
- Rate and source of heating
- Protection by an atmosphere or flux

Filler Metal Flow. As mentioned previously, wetting is only one important facet of the brazing process. A low contact angle, which implies wetting, is also a necessary but not a sufficient condition for flow. Viscosity is also important. Brazing filler metals with narrow melting ranges that are close to the eutectic composition generally have lower viscosities than those with wide melting ranges. A high surface tension of liquid filler metal, a low contact angle, and low viscosity are all desirable.

Flowability is the property of a brazing filler metal that determines the distance it will travel away from its original position, because of the action of capillary forces. To flow well, a filler metal must not gain an appreciable increase in its liquidus even though its composition is altered by the addition of the metal it has dissolved. This is important because the brazing operation is carried out at temperatures just above the liquidus of the filler metal.

The composition and surface energy of liquids and solids are assumed to remain constant. In real systems, however, these interactions occur:

- Alloy formation between liquid and base metal
- Diffusion of base metal into brazing filler metal
- Diffusion of filler metal into grains of base metal
- Penetration of filler metal along grain boundaries
- Formation of intermetallic compounds

In practice, interactions are usually minimized by selecting the proper brazing filler metal, keeping the brazing temperature as low as possible but high enough to produce flow, keeping the time of brazing temperature short, and cooling the brazed joint as quickly as possible without causing cracking or distortion.

Base Metal Characteristics. The strength of the base metal has a profound effect on the strength of the brazed joint. Therefore, this property must be carefully considered when designing the joint to have specific properties. Also, some base metals are easier to braze than others, particularly by specific brazing processes. Other factors being equal, high-strength base metals produce greater joint strengths than those made with softer base metals. When hardenable metals are brazed, joint strength becomes less predictable. This is because more complex metallurgical reactions between hardenable base metals and the brazing filler metals are involved. These reactions can cause changes in the base metal hardenability and result in lower than anticipated joint strengths. In cases where different materials make up the assembly and gaps may open or close as heating proceeds to the joining temperature, the coefficients of thermal expansion become important.

Several metallurgical phenomena influence the behavior of brazed joints and, in some instances, necessitate special procedures. These base metal effects include alloying by the brazing filler; carbide precipitation; stress cracking; hydrogen, sulfur, and phosphorus embrittlement; and oxidation stability. The extent of interaction varies greatly, depending on compositions of both the base metal and brazing filler metal and on the thermal cycle used. There is always some interaction, except in cases of mutual insolubility.

Filler Metal Characteristics. The second material involved in brazed structures is the filler metal. Strong joints can be brazed with almost any good commercial brazing filler metal if correct brazing methods and joint design are implemented. Necessary characteristics of brazing filler metals are:

- Proper fluidity at brazing temperatures to ensure flow by capillary action and to provide full alloy distribution
- Stability to avoid premature release of low-melting-point elements in the brazing filler metal
- Ability to wet the base metal joint surface
- Low volatilization of alloying elements of the brazing filler metal at brazing temperatures
- Ability to alloy or combine with the base metal to form an alloy with a higher melting temperature
- Control of washing or erosion between the brazing filler metal and the base metal within the limits required for the brazing operation

With a brazing filler metal, joint strength is dependent on joint design, brazing temperature, amount of brazing filler metal applied, location and method of application, heating rate, and many other factors that constitute the brazing technique.

The degree to which brazing filler metal interacts with and penetrates the base metal during brazing depends on the intensity of mutual diffusion processes that occur between both materials. In applications that require strong joints for high-temperature, high-stress service conditions (e.g., turbine rotor assemblies and jet engine components), it is generally wise to specify a brazing filler metal that has high diffusion and solution properties with the base metal. When the assembly is constructed of extremely thin base metals (as in honeycomb structures and some heat exchangers), good practice entails specifying a brazing filler metal that contains elements with a low-diffusion characteristic relative to the base metal being used.

Brazing Temperature. When choosing a brazing filler metal, the first selection criterion is the brazing temperature. Some brazing temperature ranges are shown in Fig. 7.4. Very few brazing filler metals possess narrow melting ranges. Brazing filler metals in which the solidus and liquidus are close together do not usually exhibit a strong tendency to coexist as a mixture of liquid and solid phases or to liquate. They flow readily and should be used with small joint clearances. As the solidus and liquidus diverge, the tendency to liquate increases, requiring greater precautions in brazing filler metal application. The mixture of solid and liquid metal can aid gap filling.

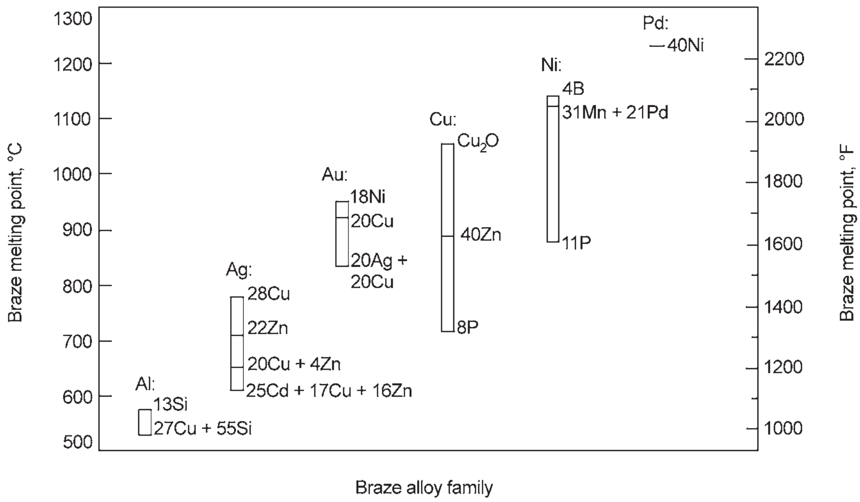

Fig. 7.4 Principal braze alloy families and their melting ranges. Source: Ref 7.4, p 7

The necessity for the brazing filler metal to melt below the solidus of the base metal is just one of several factors that affect its selection. It may be necessary for the brazing filler metal to melt below the temperature at which parts to be brazed lose strength or above the temperature at which oxides are reduced or dissociated. Joining may have to be carried out above the solution treatment temperature of the base metal, or at a structure refining temperature, or below the remelt temperature of a brazing filler metal used previously in the production of a brazed subassembly.

Liquidation. During melting, the composition of the liquid and solid filler metal phases changes as the temperature increases from the solidus to the liquidus. If the portion that melts first is allowed to flow out, then the remaining solid phases have higher temperatures than the original composition and may never melt, remaining behind as a residue, or "skull." Filler metals with narrow melting ranges do not tend to separate but flow quite freely in joints of extremely narrow clearance as long as the solution and diffusion rates of the filler metal with the base metal are low (as in aluminum brazing and the use of silver filler metal on copper). The rapid heating of filler metals with wide melting ranges or their application to the joint after the base metal reaches brazing temperature will minimize the separation or liquation. However, liquation cannot be entirely eliminated and wide-melting-range filler metals, which tend to have more sluggish flow, will require wider joint clearances and will form larger fillets at the joint extremities. A few brazing filler metals become sufficiently fluid below the actual liquidus, and satisfactory joints are achieved even though the liquidus has not been reached.

When sluggish behavior is needed, such as filling in large gaps, brazing can be accomplished within the melting range of the filler metal. However, the brazing temperature is usually 10 to 93 °C (20 to 170 °F) above the liquidus of the filler metal. The actual temperature required to produce a good joint filling is influenced by factors such as heating rate, brazing environment (atmosphere or flux), thickness of parts, thermal conductivity of the metals being joined, and type of joint to be made.

The placement of the brazing filler metal is an important design consideration, not only because the joint must be accessible to the method chosen but also because, in automatic heating setups, the filler metal must be retained in its location until molten. Brazing filler metals are available in different forms, and filler selection may depend on which form is suitable for a particular joint design.

Several general rules apply in the filler metal placement. Wherever possible, the filler metal should be placed on the most slowly heated part of the assembly to ensure complete melting. Although brazing is independent of gravity, gravity can be used to assist filler metal flow, particularly for those filler metals having wide ranges between their solidus and liquidus. Brazing filler metals can be chosen to fill wide gaps or to flow through joint configurations where the gap may vary, for example, around a corner. Unless movement between the components being joined is unimportant or can be corrected manually (through self-jigging or by using fixtures after the filler metal is molten), the filler metal should be placed outside the joint and allowed to flow into it—it should not be placed between the joint members. If erosion of thin members is possible, then the brazing filler metal should be placed on the heavier sections, which heat up more slowly, so that flow proceeds toward the thin sections. Apart from suiting the placement method selected for the joint, the form chosen for the brazing filler metal may be needed to accurately gage the amount applied, not just for economy and reproducibility but also to regulate and maintain joint properties and configuration.

Surface Preparation. A clean, oxide-free surface is imperative to ensure uniform quality and sound brazed joints. All grease, oil, dirt, and oxides must be carefully removed from the base and filler metals before brazing, because only then can uniform capillary attraction be obtained. Brazing should be done as soon as possible after the material has been cleaned. The length of time that the cleaning remains effective depends on the metals involved, atmospheric conditions, storage and handling practices, and other factors. Cleaning operations are commonly categorized as being either chemical or mechanical. Chemical cleaning is the most effective means of removing all traces of oil or grease. Trichloroethylene and trisodium phosphate are the usual cleaning agents used. Oxides and scale that cannot be eliminated by these cleaners should be removed by other chemical means. The selection of the chemical cleaning agent depends on the nature of the contaminant, the base metal, the surface condition, and the joint design. Regardless of the nature of the cleaning agent or the cleaning method used, it is important that all residue or surface film be adequately rinsed from the cleaned parts to prevent the formation of other equally undesirable films on the faying surfaces.

Objectionable surface conditions can be removed by mechanical means, such as grinding, filing, wire brushing, or any form of machining, provided that joint clearances are not disturbed. When grinding the surfaces of the parts to be brazed, care should be exercised to ensure that the coolant is clean and free from impurities to avoid grinding these impurities into the finished surfaces. When faying surfaces of parts to be brazed are prepared by blasting techniques, several factors should be considered. There are two purposes for blasting of parts to be brazed: one is to remove any oxide film, and the other is to roughen the mating surfaces in order to increase capillary attraction of the brazing filler metal. The blasting material must be clean and must not leave any deposit on the surfaces to be joined that restricts filler metal flow or impairs brazing. The particles of the blasting material should be angular rather than spherical, so that the blasted parts are lightly roughened, rather than peened, after the scale is removed. The operation should not distort or otherwise harm delicate parts. Vapor blasting and similar wet blasting methods require care because of the possibility of surface contamination. Mechanical cleaning may be adequate, in which case it should be permitted (by the design) during manufacture. In those cases that require chemical cleaning, the cleaning operation may be followed by protective electroplating, which necessitates access to the faying surface by the liquids involved.

Another surface protection technique is the use of solid and liquid brazing fluxes. At temperatures up to about 1000 °C (1830 °F), fluxes often provide the easiest method to maintain or produce surface cleanliness. In such cases, the design must not only permit easy ingress of the flux but should allow the filler metal to wash it through the joint. Above 1000 °C (1830 °F), the flux residues can be difficult to remove, and surface cleaning can be accompanied by brazing in furnaces with protective atmospheres. However, the design must permit the gas to penetrate the joint.

In addition to cleanliness and freedom from oxides, another important factor in determining the ease and evenness of brazing filler metal flow is surface roughness. Generally, a liquid that wets a smooth surface will wet a rough one even more. A rough surface will modify filler metal flow from laminar to turbulent, prolonging flow time and increasing the possibility of alloying and other interactions. Surfaces often are not truly planar, and in some instances surface roughening will improve the uniformity of the joint clearance. A rough surface features a series of crests and troughs that produce turbulent flow. These irregularities on the surface simulate grips to prevent the flow of the filler metal. Conversely, there may be a requirement that brazing filler metal not flow onto some surfaces. Stop-off materials will often avoid flow, but the design must permit easy application of the stop-off material without contaminating the surfaces to be joined. Self-fluxing filler metals, in a suitably protective environment such as vacuum, may provide the essential surface wetting.

Joint Design and Clearance. Small clearances are used because the smaller the clearance, the easier it is for capillarity to distribute the brazing filler metal throughout the joint area and the less likely it is that voids or shrinkage cavities will form as the brazing filler metal solidifies. The optimum joints are those in which the entire joint area is wetted and filled by the brazing filler metal. Typically, brazing clearances that range from 0.03 to 0.08 mm (0.001 to 0.003 in.) are designed for the best capillary action and greatest joint strength. Because brazing relies on capillary attraction, the design of a joint must provide an unobstructed and unbroken capillary path to enable the escape of flux, if used, as well as allow the brazing filler metal into the joint. In cases where filler metal is added to a joint by hand, such as by feeding in a rod or wire, the joint entry must be visible and accessible.

Some of the more important factors influencing joint design are the required strength and corrosion resistance, the necessary electrical and thermal conductivity, the materials to be joined, the mode of application of the brazing filler metal, and the postjoining inspection requirements. Consideration also should be given to the ductility of the base metal, the stress distribution in the joint, and the relative movements of the two surfaces during joining, which may introduce distortion in dimensions of the work to be brazed.

Viscosity, surface tension, and specific gravity of the brazing filler metal are not the only factors that determine the gap-filling capability of a given filler metal. Joint strength increases as joint gap decreases, down to a minimum. Table 7.1 gives the allowable joint clearances for various filler metal systems. Other factors that influence optimum joint gap with a specific brazing filler metal are joint length, brazing temperature, and base metal/filler metal metallurgical reactions.

It is important to remember that an assembly expands during heating and that the joint gap can either widen or close by the time the brazing filler metal starts to melt and move. It is desirable to design the joint to

Table 7.1 Recommended gaps for selected braze filler metals

	Joint clearance	
Brazing filler metal system	**mm**	**in.**
Al-Si alloys(a)	0.15–0.61	0.006–0.024
Mg alloys	0.10–0.25	0.004–0.010
Cu	0.00–0.05	0.000–0.002
Cu-P	0.03–0.13	0.001–0.005
Cu-Zn	0.05–0.13	0.002–0.005
Ag alloys	0.05–0.13	0.002–0.005
Au alloys	0.03–0.13	0.001–0.005
Ni-P alloys	0.00–0.03	0.000–0.001
Ni-Cr alloys(b)	0.03–0.61	0.001–0.024
Pd alloys	0.03–0.10	0.001–0.004

(a) If joint length is <6 mm (<0.240 in.), gap is 0.12 to 0.75 mm (0.005 to 0.030 in. If joint length is >6 mm (>0.240 in.), gap is 0.25 to 0.60 mm (0.010 to 0.24 in.). (b) Many different nickel brazing filler metals are available, and joint gap requirements may vary from one filler metal to another. Source: Ref 7.2

expose the solidifying filler metal to compressive, rather than tensile, stress. This is much more important in brazing than in soldering, because brazing temperatures are higher, increasing the total thermal expansion. With cylindrical joints, the components with the larger coefficient of expansion should be on the outside, whenever possible.

Although there are many kinds of brazed joints, the selection of joint type is not as complicated as it may seem, because butt and lap joints are the two fundamental types used. All other types, such as the scarf joint, are modifications of these two. Selection of joint type is influenced by the configuration of the parts, as well as by joint strength and other service requirements, such as electrical conductivity, pressure tightness, and appearance. Also influential in the selection of joint type are fabrication techniques, production quantities, and methods of feeding brazing filler metal. Lap joints are generally preferred for brazing operations, particularly when it is important that the joints be at least as strong as the weaker member. For maximum strength, lap joint length should equal three to four times the thickness of the thinner member.

Temperature and Time. The temperature of the brazing filler metal has an important effect on the wetting and alloying action, which increases with increasing temperature. The temperature must be above the melting temperature of the brazing filler metal and below the melting temperature of the parent metal. Within this range, a brazing temperature that is most satisfactory overall is generally selected. Usually, low brazing temperatures are preferred in order to economize on the heat energy required, minimize the heat effect on the base metal (e.g., annealing, grain growth, or warpage), minimize base metal/filler metal interactions, and increase the life of fixtures, jigs, or other tools. Higher brazing temperatures may be desirable so as to:

- Enable the use of a higher-melting, but more economical, brazing filler metal
- Combine annealing, stress relief, or heat treatment of the base metal with brazing
- Permit subsequent processing at elevated temperatures
- Promote base metal/filler metal interactions in order to change the composition of the brazing filler metal (this technique is usually used to increase the remelt temperature and ductility of the joint)
- Effectively remove surface contaminants and oxides within protective atmospheres brazing (also applies to pure dry hydrogen, argon, and vacuum)
- Avoid stress cracking

The time at brazing temperature also affects the wetting action. If the brazing filler metal has a tendency to creep, the joint clearance generally increases with time. The alloying action between filler metal and parent metal is, of course, a function of temperature, time, and quantity of filler metal. For production work, temperature, time, and quantity of filler metal are generally kept at a minimum, consistent with good quality, where diffusion is not required.

7.3 Brazing Filler Metals

Brazing filler metal alloy compositions can be grouped into four categories. The first and largest group is eutectic-type alloys that have aluminum, nickel, cobalt, or copper as a base, to which silicon/boron (in the case of aluminum- and nickel-base alloys) and phosphorus (in the case of copper- and nickel-base alloys) are added. The presence of one or more of these elements in the alloys tends to impart lower melting temperatures and surface tensions to the filler metal, as well as compatibility with the base material in terms of structure, composition, and properties.

The second group of brazing filler metals, which are characterized by a phase diagram that includes a peritectic reaction (for copper-tin alloys) or a minimum in the liquidus curve (for gold-nickel alloys), are used primarily in vacuum brazing applications and therefore require no alloying elements to serve as fluxing agents.

The third group of alloys, which is probably the most widely used, is based on the copper-silver binary eutectic system that is modified by substantial additions of zinc and cadmium (both providing fluxing activity) and minor additions of tin and nickel. However, applicability of cadmium-containing alloys is limited, because of more stringent restrictions by the U.S. Environmental Protection Agency on cadmium use.

The fourth group of brazing filler metal alloys consists of eutectic titanium/zirconium-based alloys to which copper and/or nickel are added. These materials are used to braze titanium-based alloys.

The first three groups of conventional brazing filler metals have been classified by the American Welding Society into seven well-defined categories (Table 7.2).

7.4 Brazing Methods

The size and value of individual assemblies, the number required, and the required rate of production will influence the selection of a heating method. Other factors to consider include the rate of heating, differential thermal gradients, and both external and internal cooling rates. These factors vary tremendously with different methods of heating, and their effects on dimensional stability, distortion, and joint structure must be considered, as outlined in Table 7.3.

7.4.1 Torch Brazing

Manual torch brazing is the brazing method most frequently used for repairs, one-of-a-kind brazing jobs, and short production runs. Any joint

Table 7.2 Major classes of brazing filler metals

Alloy family and type	AWS designation	Forms	Base materials joined	Major applications
Al-Si, eutectic	BAlSi	Preforms, wire, rods, foil, powder, RS foil(a)	Aluminum and aluminum alloys, steel to aluminum and aluminum to beryllium	Car radiators, heat exchangers, honeycomb aircraft structures, structural parts
Cu-X, solid solution Cu-Zn, peritectic Cu-Sn, peritectic	BCu RBCuZn None	Preforms, wire, rods, foil, powder, RS foil	Copper and copper alloys, copper to mild steel, copper to stainless steel	Heat exchangers, structural parts, automotive parts
Cu-P, eutectic	BCuP	Preforms, wire, rods, foil, powder, RS foil	Copper to copper, copper to silver oxide powdered metal composites	Electrical contacts, bus bars, heat exchangers
Cu-Ag, eutectic	BAg	Preforms, foil, powder	Most ferrous and nonferrous metals, except aluminum and magnesium	Most widely used utility filler metals
TM-Si-B(b), eutectic	. . .	. . .	. . .	. . .
(Ni/Fe + Cr)-Si-B	BNi	Powder, tape(c), RS foil	AlSl 300 and 400 series steels and nickel- and cobalt-base superalloys, carbon steels, low-alloy steels, and copper	Aircraft turbine components, automotive parts, heat exchangers, honeycomb structures
(Ni,Pd)-Si-B	None	Powder, tape, RS foil	AlSl 300 series stainless steels, cemented carbide, superalloys	Honeycomb structures, cemented carbide/polycrystalline diamond tools, orthodontics, catalytic converters
(Co,Cr)-Si-B	BCo	Powder, tape, RS foil	Cobalt-base heat-resistant corrosion-resistant superalloys	Aircraft engines, honeycomb marine structures
Au-Ni, solid solution	BAu	Preforms, wire, rods, foil, tape	Nickel-base heat-resistant alloys, steels	Honeycomb structures, structural turbine parts
Cu-(Ti,Zr)-Ni, eutectic and peritectic	None	Cladded strip, RS foil	Titanium/zirconium-base alloys	Titanium tubing, aircraft engines, honeycomb aircraft structures, aircraft structural parts, chemical reactors

AWS: American Welding Society. (a) May be produced as rapidly solidified (RS), ductile, amorphous/microcrystalline foil. (b) This group includes alloys based on transition metals, such as nickel, iron, and cobalt. (c) Brazing filler metal is carried on a plastic-bonded tape. Source: Ref 7.5

Table 7.3 Relative rating of selected brazing process heating methods

	Characteristics					
Method	Capital cost	Running cost	Basic output	Flux required	Versatility	Operator skill required
Torch (flame)	L/M	M/H	L	Yes	H	Yes
Electrical resistance	M	M	M/H	Yes	L	No
Induction	M/H	M	M/H	Y/N	M	No
Furnace (atmosphere)	M/H	M/H	H	Y/N	M	No
Furnace (vacuum)	H	L	H	No	M	No
Dip (flux bath)	L/M	M/H	L/M	Yes	L	No
Infrared	M	L	M	Y/N	L	No

Abbreviations: H: high; L: low; M: medium. Source: Ref 7.2

that can be accessed by a torch and brought to the brazing temperature (by the torch alone or in conjunction with auxiliary heating) can be readily torch brazed. Although any flame-producing device can be used for torch brazing, commercial applications are accomplished with the same type of torch, controls, and gases used for torch fusion welding. Conversion to brazing merely requires changes in torch nozzles and goggle lenses. The torch brazing technique is relatively simple and can be mastered by the mechanically adept in a short time. Those already experienced in torch welding and the brazing of other metals generally encounter little difficulty learning torch brazing.

Depending on the temperature and heat required, all commercial gas mixtures can be used: oxyacetylene, oxyhydrogen, oxy-natural gas, acetylene and air, hydrogen and air, propane, methane, and natural gas and air. Oxyacetylene and oxy-natural gas are the mixtures most often used commercially and are preferred in that order. Flame adjustment is very important. Generally, a slightly reducing flame is desirable in order to prevent part surfaces from oxidation. The oxyacetylene combination produces the highest temperature. The other gases are cooler, and their flames have relatively lower intensity. Thus, they are easier to use and are frequently used for light-gage material.

Manual torch brazing is particularly useful on assemblies with sections of unequal mass. As warranted by the rate of production, machine operations (Fig. 7.5) can be set up using one or more torches equipped with single or multiple flame tips. The machine can be designed to move either the work or the torches. Torch brazing can be rather easily automated with appropriate gas supplies, indexing fixtures, and cycle controls. Usually, such systems involve multiple-station rotary indexing tables. The part is fed into a holding fixture at the first station and is then indexed to one or more preheating stations, depending on the heating time required. A brazing station is next, followed by a cooling station and then an ejection station.

7.4.2 Furnace Brazing

Furnace brazing is popular because of its comparatively low equipment cost, furnace adaptability, and minimal required jigging. Furnace brazing is a low-cost process relative to other processes such as torch brazing, induction brazing, or salt-bath brazing when high-volume production output is a primary factor. Secondary factors include tooling requirements, fluxing, and cleaning requirements. With many brazing assemblies, the weight

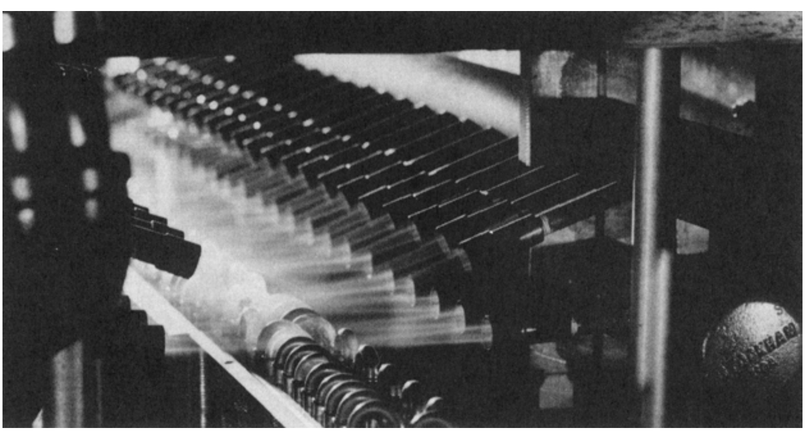

Fig. 7.5 Automated torch brazing system. Source: Ref 7.6

of the parts alone is sufficient to hold them together. Other configurations require only one or two rectangular fixturing blocks of metal. Four basic types of furnaces are used: (a) batch, with either air or controlled atmosphere; (b) continuous, with either air or controlled atmosphere; (c) retort, with controlled atmosphere; and (d) vacuum.

Furnace brazing is used extensively where the parts to be brazed can be assembled with the brazing filler metal preplaced near or in the joint. Furnace brazing is particularly applicable for high-production applications in which continuous conveyor-type furnaces are used. For medium-production work, batch-type furnaces are best. Regardless of furnace type, heating is usually produced by electrical resistance, although other types of fuel can be used in muffle-type furnaces. When continuous-type furnaces are used, several different temperature zones can be set up to provide the proper preheating, brazing, and cooling temperatures. The speed through a conveyor-type furnace must be controlled to provide the appropriate time at the brazing temperature. It is also necessary to properly support the assembly so that it does not move while traveling on the belt.

The parts should be self-jigged or fixtured and assembled with brazing filler metal preplaced near or in the joint. Fluxing is used, except in cases where a reducing atmosphere, such as hydrogen, and either exothermic or endothermic combusted gas can be introduced into the furnace. Sometimes, both flux and a reducing atmosphere are necessary. Pure and dry inert gases, such as argon and helium, are used to obtain special atmosphere properties. Fluxes should never be used when furnace brazing with a vacuum atmosphere.

A large volume of furnace brazing is performed in a vacuum atmosphere, which prevents oxidation during the heating cycle and eliminates the need for flux. Vacuum brazing is widely used in the aerospace and nuclear fields, where reactive metals are joined or where entrapped fluxes would not be tolerable. Vacuum brazing does not allow as wide a choice of brazing filler metals as does atmosphere brazing. In most cases, vacuum furnaces (Fig. 7.6) are heated by electrical resistance heaters. The overall time of a vacuum brazing operation is usually much longer than that of other batch brazing techniques and involves tying up expensive equipment for long periods to process comparatively small workloads. However, since most of the metals on which vacuum brazing excels are also costly, the use of a process that permits material economics through fabrication, while ensuring the necessary joint properties, often can be justified.

7.4.3 Induction Brazing

The high-frequency induction heating method for brazing is clean and rapid, lends itself to close control of temperature and heated area, and requires little operator skill. The workpiece is placed in or near a coil carrying alternating current (ac), which induces the heating current in the de-

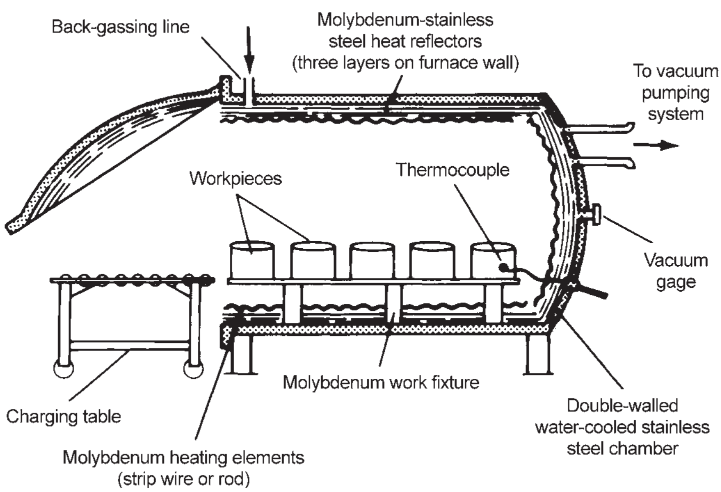

Fig. 7.6 Typical construction of horizontal side-loaded cold-wall vacuum furnace, which is ideal for brazing of small assemblies that can be placed in stacked baskets or on tiers of work grids. Source: Ref 7.1

sired area. The coils, which are water cooled, are designed specifically for each part. Therefore, heating efficiency relies on establishing the best coil design and power frequency for each application. In most cases, the coils provide heat only to the joint area. A large selection of coil designs are available (Fig. 7.7). The ability to heat selectively enables the induction method to be used when the nature of the brazement demands localized brazing.

There are several types of high-frequency sources to supply power to induction coils, each with a different range of frequencies: motor generators (5 to 10 kHz), spark-gap oscillators (20 to 30 kHz), vacuum-tube oscillators (20 to 5000 kHz), and solid-state power supplies (variable frequency). The frequency of the power source determines the type of heat that will be induced in the part. High-frequency sources produce “skin” heating, whereas lower-frequency sources provide heating in thicker areas. The brazing heat usually develops within 10 to 60 s.

Induction brazing is well suited for mass production. Mechanized brazing lines for moving assemblies to and from the coils are very common. Brazing filler metal is normally preplaced in the joint, and the brazing can be done in air with the use of a flux, in an inert atmosphere, or in a vacuum atmosphere. The rapid heating rates available with induction heating are a major advantage when using brazing filler metals that tend to vaporize or segregate.

7.4.4 Dip Brazing

Dip brazing involves immersion of assembled parts into a heated molten bath to effect brazing. The bath can be molten brazing filler metal,

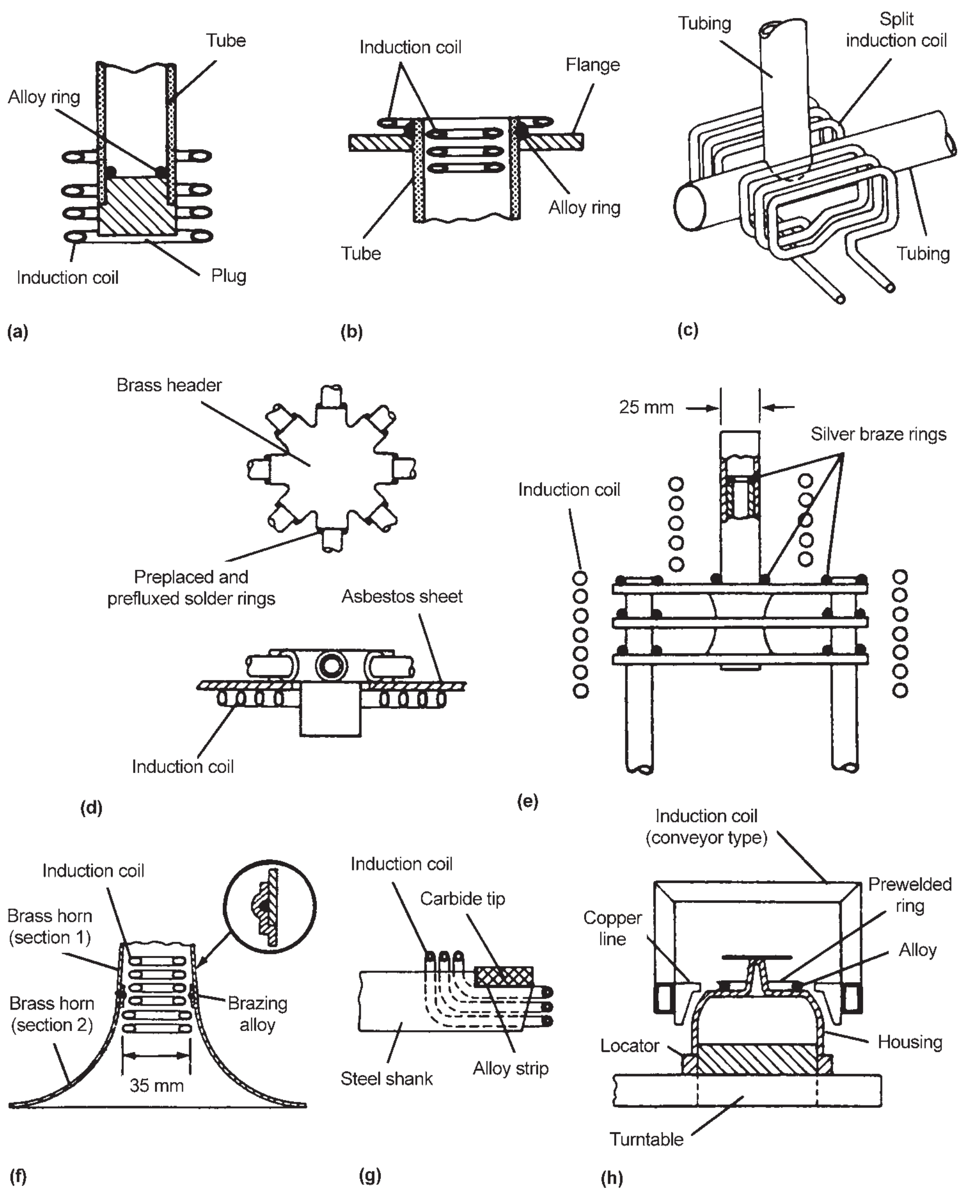

Fig. 7.7 Typical coil and joint configurations used in induction brazing: (a) solenoid coil for plug-to-tube joint (note location of brazing alloy ring), (b) internal-external coil for flange-to-tube joint (flange chamfered to assist preplaced alloy ring), (c) split solenoid coil for tube-to-tube joint (braze ring preplaced internally to provide uniform fillet), (d) pancake or pie wound coil for heating brass header to permit simultaneous brazing of eight copper tubes to header, (e) external coils for simultaneous production of a number of brazed joints, (f) formed internal coil to join two sections of musical horn (special joint design for preplacement of brazing alloy maintains smooth joint on outside of instrument, (g) open-end coil for brazing carbide tips to shanks (alloy strip preplaced as shown), and (h) conveyor-type coil for continuously brazing fuse assemblies on a rotary fixture. Source: Ref 7.7

molten chemical flux, or molten chemical salts. The molten material is contained in a "pot" furnace heated by oil, gas, or electricity. A variety of different furnace designs are shown in Fig. 7.8. In some instances, electrical-resistance heaters are used in the bath.

In molten brazing filler metal baths, the parts being joined are held together and immersed in flux-covered molten filler metal, which flows into the joints when the parts reach the bath temperature. The flux cleans the workpiece and protects the brazing filler metal by preventing oxidation and the loss of volatile elements from the bath. The pot, or crucible, used in the molten-metal method is usually made of graphite. Jigging to maintain alignment is generally necessary. Because of the difficulties of heating and containing metals at high temperatures, filler metals that require a brazing temperature >1000 °C (>1830 °F) are rarely used. Therefore, the choice of brazing filler metal is restricted to straight brasses and silver-base filler metals.

In the molten-flux method, the brazing filler metal is located in or near the joints and is heated to the required temperature by immersion in a bath of molten flux. This method is used extensively for brazing aluminum and its alloys. The flux bath provides excellent protection against metal reoxidation, which can occur quite easily with aluminum. Molten salt bath brazing has a greater scope than any other single brazing process. It can be used on as wide a range of parent metals as torch brazing but is not subject to the same maximum temperature limitations. Unfortunately, it is an inflexible process. The type of salt used for a particular application depends on the ease with which the base metal surface oxides can be removed and on the temperature required for brazing.

The dip brazing method generally causes less distortion than torch brazing because of its uniform heating. However, it may require relatively complex tooling and is therefore best used in medium-to-high production runs. This process is particularly well suited for small- to medium-sized parts with multiple hidden joints.

7.4.5 Diffusion Brazing

Diffusion brazing is a process that coalesces, or joins, metals by heating them to a suitable brazing temperature at which either a preplaced filler metal will melt and flow by capillary attraction or a liquid phase will form *in situ* between one faying surface and another. In either case, the filler metal diffuses into the base metal until the physical and mechanical properties of the joint become almost identical to those of the base metal. Pressure may or may not be applied to accomplish this. In the aerospace industry, diffusion brazing is commonly referred to by such trade names as Activated Diffusion Bonding (ADB), Activated Diffusion Healing (ADH), and Transient Liquid-Phase Bonding (TLP). In each case, the process is actually diffusion brazing.

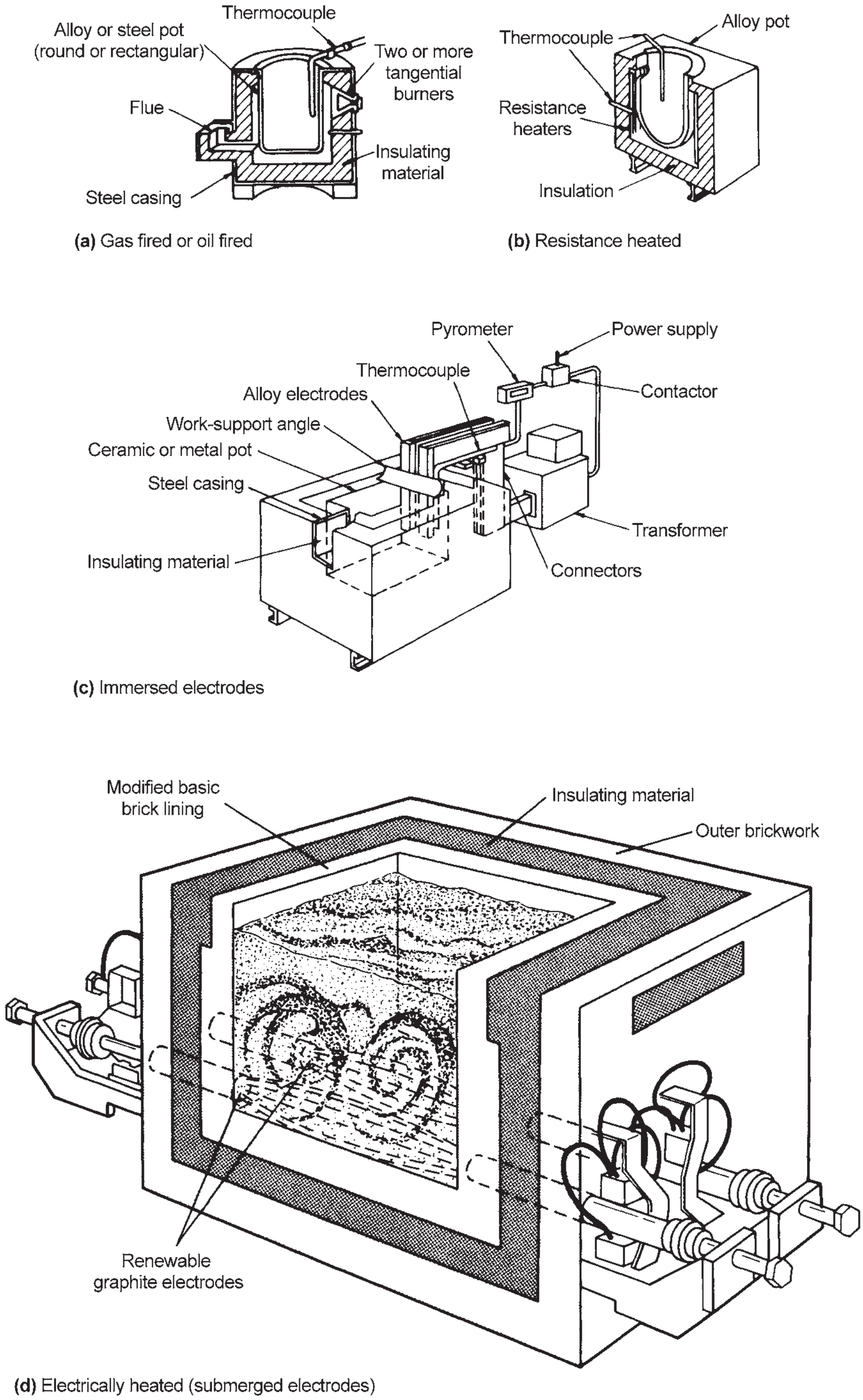

Fig. 7.8 Principal types of furnaces used for molten-salt-bath dip brazing applications: (a) and (b) externally heated; (c) and (d) internally heated.
Source: Ref 7.8

Two critical aspects of diffusion brazing are (a) a liquid filler metal must be formed and become active in the joint area, and (b) extensive diffusion of filler metal elements into the base metal must occur. This diffusion process often results in the total loss of identity of the original brazed joint (Fig. 7.9).

Although diffusion brazing is commonly performed in furnaces specifically set aside for brazing or heat treating, it is also possible to initially braze two components together by induction heating or by torch brazing and then place the brazement into a furnace for the extended diffusion cycle. This cycle can range from 30 min to 80 h or even longer. The assembly should be held at the brazing temperature long enough for one or more of the filler metal elements to adequately diffuse into the base metals, and vice versa. In this way, the mechanical properties of the brazed joint area become essentially identical to those of either or both of the base metals. The amount of diffusion that occurs will be a function of the brazing temperature, the length of time the part is held at temperature, the quantity of filler metal available for diffusion, and the mutual solubility of filler metal and the base metals. A fully diffused joint will lose all joint identity because of base metal grain growth across the entire joint.

7.4.6 Other Brazing Methods

Resistance brazing is most applicable to relatively simple joints in metals that have high electrical conductivity. In this process, the work-

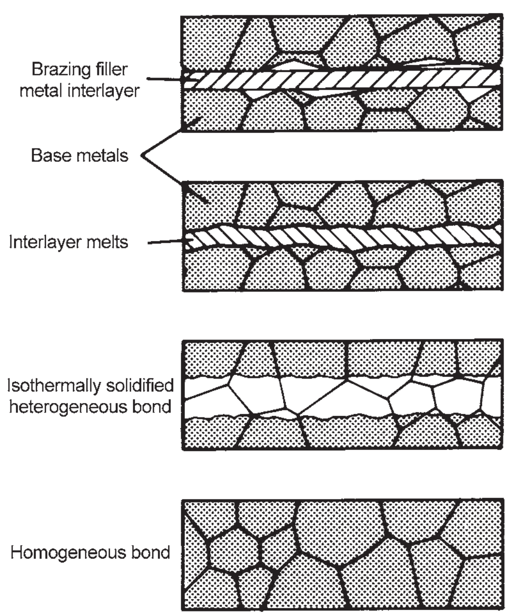

Fig. 7.9 Diffusion process resulting in loss of identity of original brazed joint. Source: Ref 7.9

pieces are heated locally. Brazing filler metal that is preplaced between the workpieces is melted by the heat obtained from its resistance to the flow of electric current through the electrodes and the workpieces. Usually, the heating current, which is normally ac, is passed through the joint itself. The joint becomes part of an electrical circuit, and the brazing heat is generated by the resistance at the joint. The equipment is the same as that used for resistance welding, and the pressure needed for establishing electrical contact across the joint is ordinarily applied through the electrodes. The electrode pressure is also the usual means for providing the tight fit needed for capillary behavior in the joint. The component parts are generally held between copper or carbon-graphite electrodes. The flux that is used must be conductive. Normally, fluxes are insulators when cool and dry but are conductive when wet. The process is generally used for low-volume production in joining electrical contacts, related electrical elements, copper commutator segments, and stainless steel tube to fittings.

Infrared (Quartz) Brazing. The development of high-intensity quartz lamps and the availability of suitable reflectors have made the infrared heat brazing technique commercially important. Infrared heat is radiant heat that is obtained with the sources having energy frequency below the red rays in the light spectrum. Although there is some visible light with every “black” source, heating is principally done by the invisible radiation. Heat sources (lamps) capable of delivering up to 5000 W of radiant energy are commercially available. The lamps do not need to follow the contour of the part in order to heat the joint area, even though the heat input varies inversely as the square of the distance from the source, unless reflectors are used to concentrate the heat. Lamps are often arranged in a toasterlike configuration, with parts traveling between two banks of lamps. Infrared brazing can concentrate large amounts of heat into small areas, which can be advantageous in certain applications. Infrared brazing setups are generally not as fast as induction brazing, but the equipment is less expensive.

Exothermic brazing is a special process but is rarely used because there are more economical production methods. In this process, the heat required to melt and flow the brazing filler metal is produced by a solid-state exothermic chemical reaction, which is defined as any reaction between two or more reactants that involves the release of large amounts of heat. Although nature provides countless numbers of these reactions, only the solid-state or nearly solid-state metal/metal oxide reactions are suitable for use in exothermic brazing units.

Electron-beam and laser brazing have been used in a limited number of applications. A laser can be used when a very small localized area of heat is required, such as for brazing small carbide tips on printer heads for electronic printers. An electron beam can be used for brazing by defocusing the beam to provide a wider area of heating. Because this is done in a vacuum, fluxes cannot be used and the brazing filler metal must be selected so that there is little or no vaporization during brazing.

Microwave Brazing. One of the newest heating methods to be developed is the use of microwaves. This technique is being used to join ceramics in high-temperature, corrosion-resistant, and high-performance applications. These applications require complex ceramics parts with strong, durable joints. The technique uses a single-mode microwave cavity. An iris controls the percentage of microwaves reflected in the cavity, and a plunger adjusts the frequency. Together, they focus microwaves on the joint. The major advantage of this technique for ceramic parts is that the entire part does not have to be heated in order to make a joint. Reheating finished ceramic parts can subject them to thermal stresses and cause cracking, which weakens the part. With microwave joining, only the interface between the pieces is heated. The technique is faster than conventional joining, which requires long times to heat ceramics uniformly. Large pieces can, in principle, be joined at a lower cost.

One disadvantage of microwave joining is that commercial equipment is only produced by a few companies, mostly for research and development purposes. Some microwave units feature 2.45 GHz single-mode or controlled multimode operation. Their cavity is designed to provide controlled-mode patterns that can focus high-energy microwave fields to heat a part only where it is needed, such as at a joint. The joint or part can be heated up to 2200 °C (3990 °F). Researchers have joined 92% Al_2O_3 ceramic parts in a 6 GHz single-mode microwave cavity at various temperatures and times. The bending strength of this joint gradually increased from the solidus of 1400 °C (2550 °F) and reached a peak of 420 MPa (60 ksi) at about 1750 °C (3180 °F).

Braze welding is a joining process in which a filler metal is melted and deposited in a specific joint configuration, and a metallurgical bond is obtained by a wetting action that is often accompanied by some degree of diffusion with the base metals. Braze welding requires heating and melting of the filler metal that has a melting temperature (liquidus) >450 °C (>840 °F).

Stringent fit-up is not critical, because the filler metal is deposited in grooves and spaces and flows into gaps wider than those used for brazing. Fabricators use braze welding as a low-temperature substitute for oxyfuel welding or as a low-cost substitute for brazing. Joint designs for braze welding are the same as for oxyfuel welding. Braze welding has been used to join cast iron, steels, copper, nickel, and nickel alloys. Compared with conventional fusion-welding processes, braze welding requires less heat input, permits higher travel speeds, and causes less distortion. Deposited filler metal is soft and ductile, providing good machinability, and residual stresses are low. The process joins brittle cast irons without extensive preheating.

Although most braze welding initially used an oxyfuel torch, copper filler metal brazing rod, and a suitable flux, current applications use carbon arc welding, gas tungsten arc welding, gas metal arc welding, or plasma arc welding without flux in the manual, semiautomatic, or automatic modes to economically bond and deposit the filler metal in the braze weld joints. However, oxyfuel welding is still widely used in machinery repair applications. Filler metal selection, proper wetting and compatibility with the base metals, and shielding from air are important to the effective use of the process with any suitable heating method.

A wide variety of parts can be braze welded using typical weld joint designs. Groove, fillet, and edge welds can be used to join simple and complex assemblies made from sheet, plate, pipe, tubing, rods, bars, castings, and forgings. Sharp corners that are easily overheated and may become points of stress concentrations should be avoided. To obtain good strength, an adequate bond area is required between filler metal and the base metal. Weld groove geometry should provide an adequate groove face area, so that the joint will not fail along the interfaces. Proper joint design selection will produce deposited filler metal strengths that may meet or exceed the minimum base metal tensile strengths. Because of the inert shielding gas, electrical arc methods have fewer included flux compounds and oxides at the faying surfaces. The result is higher joint strength and improved corrosion resistance. Original surfaces are restored by overlayers and subsequent machining.

7.5 Soldering

Soldering involves heating a joint to a suitable temperature and using a filler metal (solder) that melts at temperatures <450 °C (<840 °F). The solder is distributed between the closely fitted surfaces of the joint by capillary action. Heat is required to raise the joint to a suitable temperature and melt the solder and to promote the action of a flux on the metal surface so that the molten solder will wet and flow into the joint. Successful soldering involves shaping the parts to fit closely together, cleaning the surfaces to be joined, applying a flux, assembling the parts, and applying the heat and solder. Flux residues are removed when the joint is cooled.

7.6 Solder Alloys

The primary criterion used to select a solder is its melting properties. Alloy selection is also determined by the heat sensitivity of the substrate material, the temperature conditions that are expected during service, and the alloy's pasty range (solidus-liquidus spread). The melting characteristics of solders are determined by the solidus and the liquidus of the alloy. Solders composed of one metallic element, such as tin or indium, have a single melting temperature. Alloys with a eutectic composition also have a single melting temperature. At compositions other than the eutectic composition, the alloy will have a liquidus and a solidus. The temperature spread between the solidus and liquidus is called the pasty range, where both liquid and solid coexist. Solders are commercially available with a liquidus as low as 11 °C (51 °F) for the ternary Ga-In-Sn alloy to as high as 425 °C (795 °F) for germanium-aluminum solder.

Specifications and standards have established requirements for certain solder alloys in terms of composition limits, impurity levels, and a nomenclature for referencing particular compositions. In the United States, the specifications of solder alloy compositions are found in ASTM specification B32 and federal specification QQ-S-571E. Users in the European community use the International Organization for Standardization (ISO) specification ISO/DIS 9453.

Care should be taken in specifying the correct solder for the job, because each alloy is unique with regard to its composition and properties. When Sn-Pb solders are referred to, the tin content is customarily given first (e.g., 40%Sn-60%Pb). The compositions of tin-lead solders as well as those of Sn-Pb-Sb, Sn-Pb-Ag, and lead-silver solder compositions are listed in Table 7.4.

Table 7.4 ASTM B 32 specification for tin-lead, Sn-Pb-Sb, Sn-Pb-Ag, and lead-silver solders

	Composition(a), %											Melting range(b)			
												Solidus		Liquidus	
Alloy grade	Sn	Pb(c)	Sb	Ag	Cu	Cd	Al	Bi	As	Fe	Zn	°C	°F	°C	°F
Sn70	69.5–71.5	bal	0.50	0.015	0.08	0.001	0.005	0.25	0.03	0.02	0.005	183	361	193	377
Sn63	62.5–63.5	bal	0.50	0.015	0.08	0.001	0.005	0.25	0.03	0.02	0.005	183	361	183	361
Sn62	61.5–62.5	bal	0.50	175–2.25	0.08	0.001	0.005	0.25	0.03	0.02	0.005	179	354	189	372
Sn60	59.5–61.5	bal	0.50	0.015	0.08	0.001	0.005	0.25	0.03	0.02	0.005	183	361	190	374
Sn50	49.5–51.5	bal	0.50	0.015	0.08	0.001	0.005	0.25	0.025	0.02	0.005	183	361	216	421
Sn45	44.5–46.5	bal	0.50	0.015	0.08	0.001	0.005	0.25	0.025	0.02	0.005	183	361	227	441
Sn40A	39.5–41.5	bal	0.50	0.015	0.08	0.001	0.005	0.25	0.02	0.02	0.005	183	361	238	460
Sn40B	39.5–41.5	bal	1.8–2.4	0.015	0.08	0.001	0.005	0.25	0.02	0.02	0.005	185	365	231	448
Sn35A	34.5–36.5	bal	0.50	0.015	0.08	0.001	0.005	0.25	0.02	0.02	0.005	183	361	247	447
Sn35B	34.5–36.5	bal	1.6–2.0	0.015	0.08	0.001	0.005	0.25	0.02	0.02	0.005	185	365	243	470
Sn30A	29.5–31.5	bal	0.50	0.015	0.08	0.001	0.005	0.25	0.02	0.02	0.005	183	361	255	491
Sn30B	29.5–31.5	bal	1.4–1.8	0.015	0.08	0.001	0.005	0.25	0.02	0.02	0.005	185	365	250	482
Sn25A	24.5–26.5	bal	0.50	0.015	0.08	0.001	0.005	0.25	0.02	0.02	0.005	183	361	266	511
Sn25B	24.5–26.5	bal	1.1–1.5	0.015	0.08	0.001	0.005	0.25	0.02	0.02	0.005	185	365	263	504
Sn20A	19.5–21.5	bal	0.50	0.015	0.08	0.001	0.005	0.25	0.02	0.02	0.005	183	361	277	531
Sn20B	19.5–21.5	bal	0.8–1.2	0.015	0.08	0.001	0.005	0.25	0.02	0.02	0.005	184	363	270	517
Sn15	14.5–16.5	bal	0.50	0.015	0.08	0.001	0.005	0.25	0.02	0.02	0.005	225	437	290	554
Sn10A	9.0–11.0	bal	0.50	0.015	0.08	0.001	0.005	0.25	0.02	0.02	0.005	268	514	302	576
Sn10B	9.0–11.0	bal	0.20	1.7–2.4	0.08	0.001	0.005	0.03	0.02	0.02	0.005	268	514	299	570
Sn5	4.5–5.5	bal	0.50	0.015	0.08	0.001	0.005	0.25	0.02	0.02	0.005	308	586	312	594
Sn2	1.5–2.5	bal	0.50	0.015	0.08	0.001	0.005	0.25	0.02	0.02	0.005	316	601	322	611
Ag1.5	0.75–1.25	bal	0.40	1.3–1.7	0.30	0.001	0.005	0.25	0.02	0.02	0.005	309	588	309	588
Ag2.5	0.25	bal	0.40	2.3–2.7	0.30	0.001	0.005	0.25	0.02	0.02	0.005	304	580	304	580

(a) Limits are maximum percentages, unless shown as a range or stated otherwise. For purposes of determining conformance to these limits, an observed value or calculated value obtained from analysis shall be rounded to the nearest unit in the last right-hand place of figures used in expressing the specified limit, in accordance with the rounding method of ASTM Recommended Practice B 29. (b) Temperatures given are approximations and are for information only. (c) Balance—remaining percentage is made up of lead. Source: Ref 7.1

Tin-Lead Solders. Solders in the tin-lead system are the most widely used of all joining materials. Industrial soldering alloys contain combinations from 100% Sn to 100% Pb, as demanded by the particular application. The utility of the tin-lead combination is highlighted by examination of the phase diagram between these two materials (Fig. 7.10). Tin-lead solder alloys can be obtained with melting temperatures as low as 180 °C (360 °F) and as high as 315 °C (600 °F). Except for the pure metals and the eutectic solder at 63%Sn-37%Pb, all soldering alloys melt within a temperature range that varies according to the alloy composition. Each alloy has unique characteristics. In general, properties are influenced by the melting characteristics of the alloys, which in some measure are related to their load-carrying and temperature capabilities.

Soldering alloys containing <5% Sn are used for joining tin-plated containers and for automobile radiator manufacture. For automobiles, a small additional amount of silver is usually added to provide extra joint strength at automobile radiator operating temperatures. Soldering alloys of 10%Sn-90%Pb and 20%Sn-80%Pb are also used in radiator joints. With compositions between 10%Sn-90%Pb and 25%Sn-75%Pb, care must be taken to avoid any kind of movement during the solidification phase to prevent hot tearing in solders with a wide freezing range, as indicated by the phase diagram in Fig. 7.10.

Higher-tin-content solders at the 25%Sn-75%Pb and 30%Sn-70%Pb compositions have a lower liquidus and can be used for joining materials with sensitivity to high temperatures or where the wetting characteristics of the tin are important to providing sound soldered joints. Solder alloys in the composition range described above usually are applicable to industrial products and generally are used in conjunction with inorganic fluxing materials.

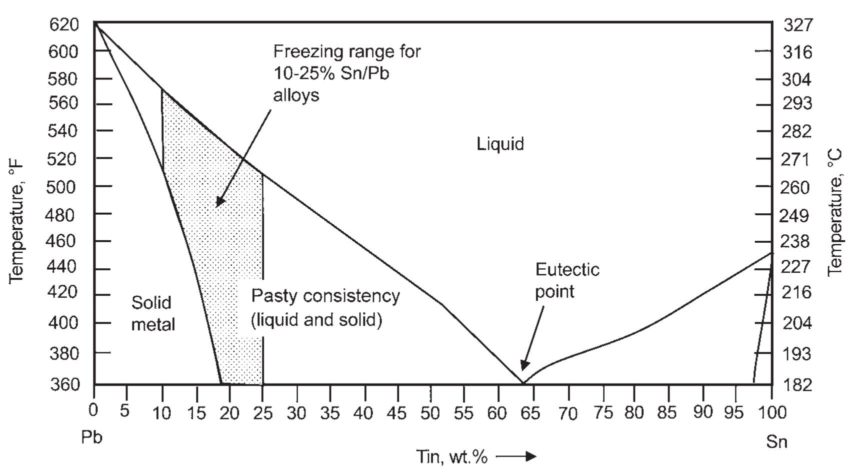

Fig. 7.10 Tin-lead phase diagram Source: Ref 7.10

The widely used general-purpose solder alloys contain 40 to 50% Sn. These solders are used for plumbing applications, electrical connections, and general soldering of domestic items. The 60%Sn-40%Pb and 63%Sn-37%Pb alloys are used most extensively in the electronic industries.

Lead-Free Solders. Lead is well known as a toxic metal. Past uses of lead and lead chemicals in water-supply plumbing, paint, and gasoline resulted in a measurable increase of lead in the environment and, as a consequence, increased blood levels of lead in humans. Paint chip ingestion, mainly by children, resulted in numerous cases of lead poisoning. Consequently, the use of lead in these applications has been prohibited for several years. The primary concern now is from groundwater leaching of lead-bearing solder in electronic products ultimately disposed in landfills. The use of lead in electronics has come under increasing scrutiny. Given the trends in both Europe and Japan, it is inevitable that the United States will be forced to phase out lead in electronics use.

Eutectic or near-eutectic tin-lead solder with a melting temperature of 183 °C (360 °F) has been the solder alloy material of choice for decades in the electronics industry. Eutectic tin-lead solder alloy provides outstanding solderability and forms stable solder joints capable of operating in a wide variety of service environments. It is easy to use, and because it has a relatively low melting temperature, rework and repair are also easy. Because of the toxicity of lead and the concern that the lead in electronic products may end up in landfills—and thus ultimately wind up in the water supply—the electronic industry developed alternative solder alloys that do not contain lead. These alternative solder alloys are typically composed of tin with one, two, or three additives, such as copper, silver, bismuth, antimony, zinc, or indium (Table 7.5). Some of these are more suitable for wave soldering, and others are more suitable for reflow soldering. Most lead-free solders have a melting temperature >215 °C (>420 °F). Components and the personal computer (printed card) board material need to be able to withstand these higher soldering temperatures. Since all lead-free solders exhibit poorer wettability compared with tin-lead solders, solder defects may increase, requiring additional rework. Flux activators in solder paste and wave solder flux must be designed to function properly at higher soldering reflow temperatures. Higher reflow oven temperatures equate to higher energy use and energy costs. Generally, the lead-free solder alloys require a higher reflow profile because of the higher melting temperature of the alloys. The melting temperature of the Sn-Ag-Cu eutectic is 217 °C (423 °F), whereas the melting temperature of the Sn-Pb eutectic is 183 °C (360 °F). This exposes the printed wiring board (PWB) and the components to higher temperatures during assembly and thus compromises their subsequent reliability. Board and component metallization need to be lead free. Since lead-free solder joints differ from tin-lead in appearance, quality guidelines for visual inspection require modification.

Table 7.5 Lead-free solder families

Composition	Meltimg temperature, °C	Comments
Sn-0.7Cu	227	Recommended for wave soldering applications
Sn-3.5Ag	221	Wetting inferior to Sn-Agu-Cu but used where higher melting temperature is required
Sn-3.5Ag-0.7Cu	217	Most widely used lead-free alloy. Various percentages of silver and copper are used. Recommended by NEMI for surface mount
Sn-Ag-Bi Sn-Ag-Bi-Cu	210 215	Better wetting properties than Sn-Agu-Cu but must not be used with lead. Mainly used as solder paste but has been used for wave soldering, mainly in Japan. Wire not available, so rework difficult
Sn-9Zn	199	Zinc-containing alloys are difficult to use, need special fluxes, and are susceptible to corrosion. New solder pastes with reasonable soldering performance have recently been developed.
Sn-8Zn-3Bi	191	Used by several Japanese manufacturerds where heat-sensitive components are used. Paste made by Senju. Difficult to use, needs nitrogen for SMT
58bI-42sN	138	Low melting temperature, hard, brittle alloy but performed well in reliability trials

NEMI, National Electronics Manufacturing Initiative; STM, surface mount technology. Source: Ref 7.1

The Sn-Ag-Cu alloys are the mainstream alloy systems that will replace Sn-Pb. This family of alloys is near eutectic, with acceptable thermal fatigue properties, strength, and wettability. They can be used to mount parts by reflow, flow, and manual soldering. The alloys have excellent heat resistance. Its creep resistance at 125 °C (257 °F) is 3850 h, compared with 1 h for the Sn-Pb alloy, thus indicating good thermal fatigue and creep resistance. These alloys are easily worked into various shapes and supplied in many forms, including bar, paste, wire, cored wire, ball, and preforms. Potential problems with these alloys include a higher melting temperature (36 °C or 65 °F higher than that of conventional Sn-Pb alloy), and its silver content means that the price is dependent on the spot price of silver.

The major problems with the Sn-Cu low-cost alloys are their high melting temperatures, poor wettability, low resistance to thermal stress, and poor creep resistance. However, as a result of its low cost, it is being used for flow soldering of single-sided printed circuit boards that require relatively large amounts of solder. Studies have shown that trace amounts of nickel, phosphorus, and germanium improve the oxidation resistance. This alloy has the disadvantages of a higher melting temperature than the Sn-Ag-Cu alloys and may corrode iron-containing solder pots.

The Sn-Ag-Bi composition was found by NEMI (National Electronics Manufacturing Initiative) and the National Institute of Standards and Technology to have exceptional thermal fatigue performance, better wetting, and a lower melting temperature than the Sn-Ag-Cu group of alloys. However, if any lead is present on component terminations or personal computer board pads, a low-melting ternary Sn-Pb-Bi phase can form that has a melting temperature of only 96 °C (205 °F). Therefore, NEMI has recommended that general use of this alloy should be avoided until it is assured that lead on component terminations and board pads has been completely phased out, perhaps 7 to 10 years.

The Sn-Bi eutectic has a low melting temperature (139 °C, or 282 °F) and is therefore well suited for mounting parts having low heat resistance. However, bismuth is not very ductile. A strong impact has been known to cause the soldered area to peel off. Examination of the fracture surface revealed a brittle fracture mode. The bismuth addition decreases the melting temperature and enhances the wettability by reducing the surface tension. A number of solder products with 1 to 3% have been produced, though reliability and wettability must be considered if they are to be used.

The biggest advantage of the Sn-Zn alloy is its lower melting temperature. Although there are many lead-free solders on the market, the melting temperature of the Sn-Zn alloy is closest to that of the Sn-Pb alloy. The melting temperature of the Sn-Zn eutectic is 199 °C (390 °F). With the Sn-8Zn-3Bi alloy type, the solidus is low (189 °C, or 372 °F), and the working temperature can therefore be kept low as well. The Sn-Zn alloys is thus advantageous because components that are currently used with Sn-Pb solder can also be used with the Sn-Zn alloy. However, because zinc has traditionally been treated as an impurity in Sn-Pb solder, many problems remain to be resolved. Wettability is a problem with zinc, because it forms a strong, stable oxide film. Although this problem can possibly be solved by a new flux, a nitrogen gas atmosphere is almost certainly required. The strong ionization tendency of zinc means high reactivity with organic acids, and this degrades storage stability. An important point in the application of the Sn-Zn alloy is the establishment of a recycling system. When it contaminates other metals, zinc hinders recycling.

The main difference between Sn-Pb and the most commonly used lead-free solders is the higher melting temperatures of the lead-free solders. Increased temperature can damage components and laminate and so it is important to:

- Use as low a temperature as possible.
- Avoid heat sensitive components. Damage includes plastics melting, delamination of integrated circuits, cracking of brittle ceramic devices, and loss of fluid from electrolytic capacitors.
- Consider using a laminate with high glass transition temperature (T_g) for thicker printed card boards with many layers and large high-thermal-mass components. Laminate damage can include warping, delamination, and cracks in plated-through holes.

Lead-free solders are more aggressive to steels and can damage internal parts of ovens, particularly if solders containing silver are used. Some but not all wave soldering machines can be modified to operate with lead-free solders.

A suitable lead-free flux is required since lead-free processes operate at higher temperatures, so fluxes designed for tin-lead will be consumed and much less effective at the higher temperature at which lead-free solder wetting occurs.

Even though the adaptation of lead-free solders is inevitable, there are still legitimate concerns for critical electronic components (i.e., aerospace, defense, and medical) that must function reliably for decades. Among these are the occurrence of tin whiskers and tin pests. Lead-free solders are prone to the formation of tin whiskers, and the likelihood of tin whisker formation increases with tin content. Tin whiskers (Fig. 7.11) appear as thin strands of tin caused by a spontaneous growth from the surfaces of tin alloys, believed to initiate from compressive stress and a break in the tin oxide layer. The stress can originate from oxidation, thermal cycling, intermetallic layer formation, and mechanical processes. Furthermore, tin whiskers can arise from the solder alloys, surface finishes, or component finishes. The formation of tin whiskers on printed circuit boards is especially detrimental in that it can form an alternative conductive path, creating short circuits and resulting in component failure. Lead acts to suppress the formation of tin whiskers, so this issue was not widely problematic before the restrictions on use of lead came into action.

Tin pests are the crystallographic transformation of tin at low temperatures. Tin is an allotropic material, meaning that it has more than one crystal form. The beta (β) form is the common white and useful form of tin. The alpha (α) form is the uncommon form of tin that manifests as gray and extremely brittle. The transformation of β-tin to α-tin is accompanied by an increase in volume and will occur at temperatures <13 °C (<55 °F). Tin pests result in a decrease in electrical conductivity and loss of joint integrity. Given that tin pests usually begin to occur in colder temperatures, it is important to assess the possible temperature conditions that the solder will be exposed to in service, and conduct appropriate reliability tests using these conditions to determine potential tin pest susceptibility.

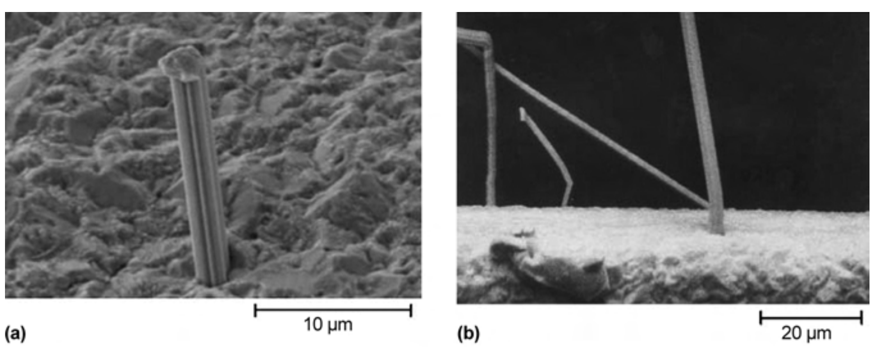

Fig. 7.11 Tin whisker morphologies: (a) a fluted whisker on Sn-Cu finish surface, and (b) many other whiskers bent at a sharp angle. Source: Ref 7.11, p 148

It is also important that the replacement of lead in electronic solders will render useless the reliability data for electronics assemblies gathered over the last 50 years. The reliability of Sn-Pb solder joints is well understood. Using Coffin-Manson curves and Weibull distribution plots of thermally cycled solder joints, it is possible to estimate the amount of useful life remaining for Sn-Pb solder joints after exposure to a known number of thermal cycles.

Other Solder Alloys. A wide range of alternate alloys are available. At low temperatures, the ternary Ga-In-Sn eutectic (62.5%Ga-16%Sn-21.5%In), with a melting temperature of 10 °C (50 °F), is useful. Bismuth-base fusible alloys with melting temperatures ranging from 45 to 250 °C (110 to 485 °F) are available. Alloys based on indium with lead, tin, and silver additions are available to cover the temperature range from 95 to 315 °C (200 to 600 °F). Solders available in the temperature range from 315 to 400 °C (600 to 750 °F) are limited, but combinations available include cadmium-zinc and cadmium-silver alloys (liquidus from 265 to 400 °C, or 510 to 750 °F), the zinc-aluminum eutectic (liquidus 380 °C, or 720 °F), and three gold-base solders: the gold-tin eutectic at 80%Au-20%Sn, with a melting temperature of 280 °C (535 °F); the gold-germanium eutectic at 88%Au-12%Ge, with a melting temperature of 355 °C (675 °F); and the gold-silicon eutectic at 96.4%Au-3.6%Si, with a melting temperature of 355 °C (700 °F). The temperature range from 400 to 450 °C (750 to 840 °F) is limited to the only available alloy, the aluminum-germanium eutectic (45%Al-55%Ge), with a melting temperature of 425 °C (795 °F). The gold-indium composition (82%Au-18%In), with a liquidus of 485 °C (905 °F) and a solidus of 450 °C (845 °F), is occasionally used.

Impurities in solders can affect their performance and must be kept to a minimum. ASTM standards for solder alloys set maximum tolerable impurities in alloys as provided by the supplier or refinery. Impurities can also be inadvertently picked up during normal use, especially with use of solder pots with recirculation systems and passage of components through molten materials. The purity of solders supplied by reputable manufacturers usually is adequate for most applications. Particular soldering operations may require the use of superpure materials that can be supplied upon request. Impurities present in sufficient quantities can affect wetting properties, flow within the joint, melting temperature of the solder, strength capabilities of joints, and oxidation characteristics of the soldering alloys.

7.7 Base Metal Selection

A sound soldered joint is achieved by selecting and using the proper materials and processes. Base metals are usually selected to achieve the specific property requirements of a component. These properties can include strength, ductility, electrical conductivity, weight, and corrosion resistance. When soldering is required, the solderability of the base materials should also be a selection factor. Some guidelines as to the relative solderability of different metals and alloys are (Ref 7.10):

Easy to solder	Less easy to solder	Difficult to solder	Very difficult to solder	Most difficult to solder	Not solderable
• Platinum • Gold • Copper • Silver • Cadmium plate • Tin • Solder plate	• Lead • Nickel plate • Brass • Bronze • Rhodium • Beryllium copper	• Galvanized iron • Tin-nickel • Nickel-iron • Mild steel	• Chromium • Nickel-chromium • Nickel-copper • Stainless steel	• Aluminum • Aluminum bronze	• Beryllium • Titanium

Both flux selection and surface preparation will be affected by the solderability of the base materials to be joined.

The solderability of metals and alloys is not simply a matter of chemical nobility, as might be supposed when regarding the good solderability of the noble metals, which do not readily form oxide or tarnish films. Although cadmium and tin both form oxides readily, they are considered easy to solder. On the other hand, chromium, nickel, and aluminum also form oxide films readily but are difficult to solder. The difference is in the extremely adherent, protective nature of the oxides formed on chromium, nickel, and aluminum, compared with the oxides that form on tin and cadmium. Chromium, nickel, and aluminum are all soldered regularly with good results, but special attention must be given to the selection of fluxes, which must be very active. In many cases, the use of active fluxes is either restricted or not allowed. Therefore, these hard-to-solder metals and alloys always require special consideration to provide reproducible soldering.

7.8 Precleaning and Surface Preparation

Oil, film, grease, tarnish, paint, pencil markings, cutting lubricants, and general atmospheric dirt interfere with the soldering process. A clean surface is imperative to ensure a sound and uniform-quality soldered joint. Fluxing alone cannot substitute for inadequate precleaning. Therefore, a variety of techniques are used to clean and prepare the surfaces of metals to be soldered. The importance of cleanness and surface preparation cannot be overemphasized. These steps help ensure sound soldered joints, as well as a rapid production rate. Precleaning can also greatly reduce repair work due to defective soldered joints. Two general methods of cleaning are chemical and mechanical. The most common of these are degreasing, acid cleaning, mechanical cleaning with abrasives, and chemical etching.

Coating the base metal surfaces with a more easily soldered metal or alloy before the soldering operation can facilitate soldering. Coatings of tin, copper, silver, cadmium, iron, nickel, and the alloys of tin-lead, tin-zinc, tin-copper, and tin-nickel are used for this purpose. The precoating of metals that have tenacious oxide films (e.g., aluminum, aluminum bronzes, stainless steels, and cast iron) is almost mandatory. The precoating of steel, brass, and copper, although not entirely essential, is of great value in some applications.

7.9 Fluxes

A flux promotes solder wetting of the base metal by removing tarnish films from precleaned surfaces, thereby permitting the molten solder to react with the base metal and to spread, by preventing oxidation of the base metal during the heating steps just before soldering, and by lowering the surface tension of the solder, allowing it to more readily fill gaps and holes by capillary action.

Fluxes contain three principal ingredients: (a) an active chemical compound, such as a halide, for oxide removal, (b) wetting agents to improve surface coverage, and (c) a vehicle to dilute and mix the cleaning compound and wetting agents together. The vehicle, which is removed by evaporation during the soldering process, is typically water, isopropyl alcohol, glycerin, glycol (for liquid fluxes), or petroleum jelly (for flux pastes or creams). Fluxes are characterized by their cleaning agent and are assigned to one of these categories of increasing activity: rosin-base fluxes, organic acid fluxes (also called intermediate or water-soluble fluxes), and inorganic acid fluxes. After the soldering operation, any residue left by these fluxes should be removed to avoid corrosion damage to the joint.

Rosin-base fluxes contain "water-white" rosin, a distillation product from pine tree sap. When used alone, rosin-base fluxes are referred to as a "nonactivated," or type R, grade. The addition of an activator to rosin fluxes increases their chemical activity. Activators can be organic halogenated compounds, such as amine hydrohalides that contain chloride, fluoride, or bromide ion groups, or "halide-free" activators, such as oleic, stearic, or lactic acids. Halide-free fluxes are recommended for materials that are sensitive to stress corrosion cracking. The concentration of activators, which defines the corrosivity of the flux, determines the flux category as rosin-base, mildly activated (RMA), fully activated (RA), or superactivated (SA). The R and RMA fluxes are used on electronic assemblies and systems. The RA and SA fluxes are used on base metals such as nickel (and nickel plate), lightly tarnished low-carbon steels, copper, iron-base alloys, and copper-base alloys (brasses, bronzes, and beryllium copper).

Organic acid fluxes contain one or more organic acids, such as lactic, oleic, or stearic acid. Chemical activity can be enhanced by adding organic halogen compounds (amine hydrohalide, which may contain chloride and bromide derivatives) or nonhalogenated substances, such as one of the amines or amides (urea or ethylene diamine). Typical vehicles include water, isopropyl alcohol, polyglycols, or petroleum jelly for pastes.

The organic acid fluxes are used in many electronic applications involving machine processes and hand assembly, as well as the hot tin or solder dipping of nickel and iron-base alloy leads and devices. These fluxes are also used on structural applications with copper and copper alloy workpieces that have light to moderate tarnishes.

Inorganic acid fluxes have the highest levels of chemical activity. There are two categories of these fluxes: (a) pure acids, such as hydrochloric, hydrofluoric, or phosphoric acids, which have surfactants added to enhance coverage, and (b) inorganic salt mixtures or solutions, which may also contain surfactants. The inorganic acid fluxes are limited to structural applications, such as plumbing or mechanical assemblies. Their corrosive activity is unacceptable for electronic devices or substrates or for their assembly. These fluxes are effective on nickel and nickel alloys, stainless steels, chromium, and heavily tarnished copper and copper alloys.

7.10 Solder Joint Design

Solder alloys generally have lower-strength properties than the materials to which they will be joined. Overall design of a product involving soldered joints must therefore be evaluated to ensure that the joints can carry the supplied loads for the expected life of the product. Stress rupture and creep properties are therefore important to solder joints under load in service. Care must be taken also not to use bulk solder properties for this evaluation, because these do not take into account the effect of joint formation, interfacial solder joint reactions, and stress transfer capabilities across soldered joints. In designing a product, several solder/base metal selections can be made that will adequately perform the task. In addition to design aspects, overall costs of materials and of manufacturing the product are usually taken into account. The lap joint provides a capability for conservative design by allowing larger areas of joints to be used at lower unit stress. Most data available in the literature on joint strengths are not directly applicable to the design of a soldered joint. It is often necessary to fabricate sample parts and test the joints to ensure their producibility. Various joint designs are shown in Fig. 7.12.

7.11 Solder Heating Methods

In addition to surface preparation, solder selection, and fluxing, another important part of the soldering process is the choice of heating method. Available methods include:

- Soldering iron or bit
- Flame or torch soldering
- Hot dip soldering

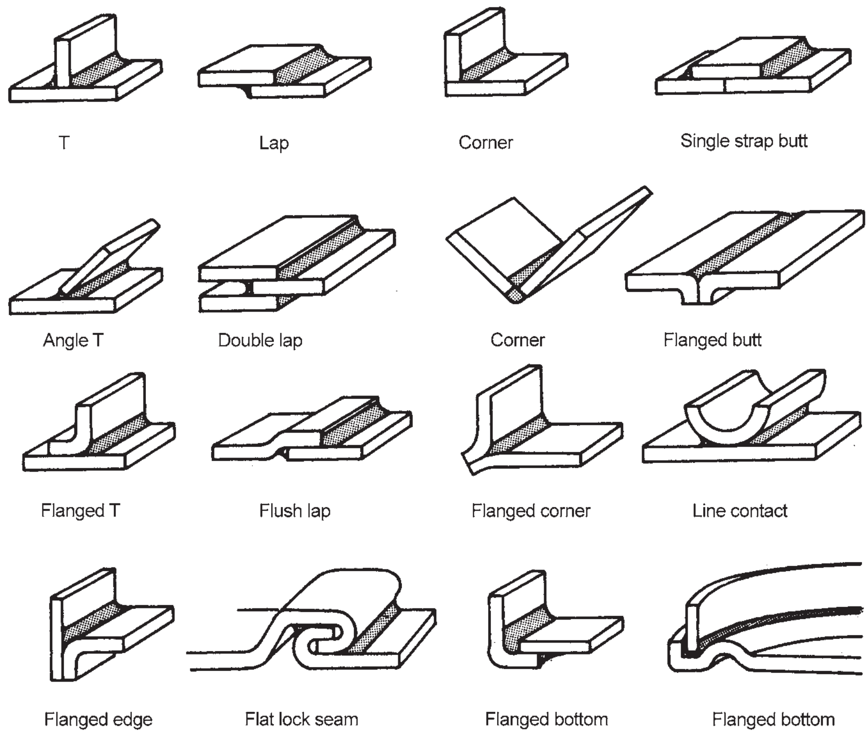

Fig. 7.12 Joint designs frequently used in soldering. Source: Ref 7.10

- Induction soldering
- Resistance soldering
- Furnace soldering
- Infrared soldering
- Ultrasonic soldering
- Wave soldering
- Laser soldering
- Hot gas soldering
- Vapor-phase soldering

The proper application of heat is of paramount importance in any soldering operation. The solder should melt while the surface is heated to permit the molten solder to wet and flow over the surface. Heating method selection is therefore an important consideration.

Soldering Irons. The traditional soldering tool is the soldering iron, or bit, with a copper tip than can be heated electrically, by direct flame, or in an oven. Because soldering is a heat transfer process, the maximum surface area of the heated tip should contact the base metal. The solder itself should not be melted on the tip of the iron when a joint is being made. To lengthen the usable life of a copper tip, a coating of solder-wettable metal, such as iron with or without additional coatings, is applied to the surface of the copper. The rate of dissolution of the iron coating in molten solder is substantially less than the rate for copper. The iron coating also shows less wear, oxidation, and pitting than does uncoated copper.

Soldering irons are available in a large variety of sizes and designs, ranging from a small pencil to special irons or bits that weigh ≥2 kg (≥5 lb). The selection of the iron depends on the application and the quantity of heat needed at the joint. The heat recovery time of the iron should be fast enough to keep up with the job. Regardless of the heating method, the tip performs the following functions: storing and conducting heat from the heat source to the parts being soldered, storing molten solder, conveying molten solder, withdrawing surplus molten solder, and heating the workpiece joint area to the soldering temperature.

The angle at which the copper tip is applied to the work is important in terms of delivering maximum heat. The flat side of the tip should be applied to the work to obtain the maximum area of contact. Flux-cored solders should not be melted on the soldering tip, because this destroys the effectiveness of the flux. The cored solder should be touched to the soldering tip to initiate good heat transfer, and then the solder should be melted on the work parts to complete the solder joint.

Torch Soldering. The selection of a gas torch is controlled by the size, mass, and configuration of the assembly to be soldered. When fast soldering is necessary, a flame is frequently used. The flame temperature is controlled by the fuel mixture used. Fuel gas burned with oxygen gives the highest flame temperature possible with the selected gas. The highest flame temperatures are attained with acetylene. Lower temperatures are obtained with propane, butane, natural gas, and manufactured gas. Multiple flame tips, or burners, often have shapes that are suitable to the work. They can be designed to operate on oxygen and fuel gas, compressed air and fuel gas, or Bunsen-type torches. When adjusting tips or torches, care should be taken to avoid adjustments that result in a "sooty" flame, because the carbon deposited on the work will prevent the flow of solder.

Dip soldering uses a molten bath of solder to supply both the heat and solder required to produce the joints. This method is useful and economical because an entire unit comprising any number of joints can be soldered in one operation after proper cleaning and fluxing. Fixtures are required to contain the unit and maintain proper joint clearances during solder solidification. The soldering pot should be large enough that, at a given rate of production, the units being dipped will not appreciably lower the temperature of the solder bath.

Wave Soldering. Wave soldering is one of the primary techniques for the mass assembly of printed wiring boards involving through holes, surface mount devices, or a combination of these two technologies. A schematic of the wave soldering process is shown in Fig. 7.13. A solder "fountain" or "wave" is created by a pump located at the bottom of the solder

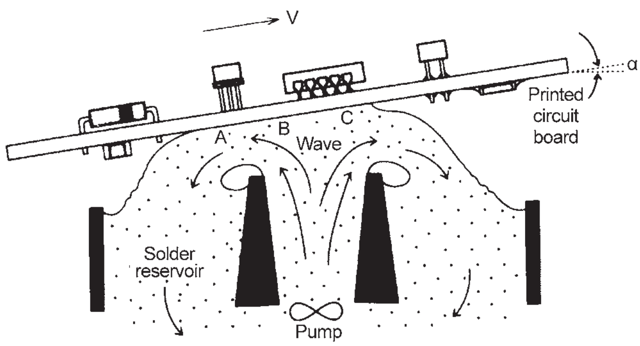

Fig. 7.13 Schematic of the wave soldering process. The three important process control regions are: (A) entry, (B) interior, and (C) peel-back region. The *v* is velocity of printed circuit board. Source: Ref 7.12

pot; suitable baffles are mounted in the pot to direct the flow of solder into the desired configuration. The printed wiring board is placed onto a conveyor, which brings it into contact with the wave surface. Note from Fig. 7.13 that the circuit boards travel along the surface of the solder; molten alloy does not flow on top of the board. As the printed circuit board passes on the wave, the solder wets the surface mount package leads, terminations, and exposed metal surfaces in the circuit board, and also fills plated through holes. This technique can produce several thousand solder joints in a matter of minutes.

The implementation of wave soldering for surface-mount technology requires that the devices be glued to the substrate prior to wave soldering. Moreover, the entire surface-mount package must be able to withstand contact with the flux and temperatures of the molten solder without a loss of reliability. Small-outline transistors and discrete components (chip resistors, capacitors, etc.) are readily attached by wave soldering; larger packages (e.g., leaded or leadless chip carriers) may be damaged by exposure to the harsh environments (flux and molten solder) as well as be more prone to solder defects.

The wave soldering technique encompasses a sequence of processes, all of which are typically contained in the same apparatus. First, the substrate receives a coating of flux. Flux application methods include:

- A wave technique similar to that shown in Fig. 7.13
- Coating the circuit board by a flux foam created by passing air or nitrogen through the flux bath to generate the foam (or froth) on the bath surface
- Directly spraying flux onto the board surface

After flux is applied, the substrate is passed through a preheating stage. Warming the board promotes activation of the flux, accelerates the evaporation of volatiles from the flux which can cause voids and solder balls by spattering upon contact with the hot solder bath, and reduces thermal shock to the substrate and devices when it passes onto the solder wave. Then, the circuit board contacts the solder wave for the formation of the joints. After passing the wave, the board cools through natural heat loss or, more quickly, by the use of forced air.

Induction Soldering. The only requirement for a material that is to be induction soldered is that it be an electrical conductor. Like induction brazing, the rate of heating depends on the induced current flow. The distribution of heat obtained with induction heating is a function of the induced current frequency. The higher frequencies concentrate the heat at the surface of the workpiece. Several types of equipment are available for induction heating: the vacuum tube oscillator, the resonant spark gap, the motor-generator unit, and solid-state units. Induction heating is generally applicable for soldering operations, with the following requirements and attributes: large-scale production, application of heat to a localized area, minimum oxidation of surface adjacent to the joint, good appearance and consistently high joint quality, and simple joint design that lends itself to mechanization.

The induction technique requires that the parts being joined have clean surfaces and that joint clearances be maintained accurately. High-grade solders are generally required to obtain rapid spreading and good capillary flow. Preforms often afford the best means of supplying the correct amount of solder and flux to the joint. When induction soldering dissimilar metals (particularly joints composed of both magnetic and nonmagnetic components), attention must be given to the design of the induction coil in order to bring both parts to approximately the same temperature.

Furnace Soldering. In many applications, especially in high-production soldering, a furnace will produce consistent and satisfactory soldering. Although this method is not widely used, furnace heating should be considered when: (a) entire assemblies can be brought to the soldering temperature without damage to any of the components, (b) production is sufficiently large to allow expenditures for jigs and fixtures to hold the parts during the soldering process, and (c) the assembly is complicated in nature, making other heating methods impractical.

Proper clamping fixtures are important during furnace soldering. Movement of the joint during solder solidification can result in a poor joint. Another consideration in furnace soldering is flux selection. Rosin and organic fluxes are subject to decomposition when maintained at elevated temperatures for an extended period of time. When either rosin or organic flux is used, the part must be brought rapidly to the liquidus of the solder. It is sometimes beneficial to dip the parts in a hot flux solution before placing them in the oven. When using rosin-base flux, it is generally necessary to use a solder with ≥50% tin content. The reducing atmosphere used in the furnace does not allow joints to be made without flux, because the temperatures at which these atmospheres become reducing are far above the liquidus of the solders. The use of inert atmospheres will prevent further oxidation of the parts, but flux must be used to remove the oxide that is already present. The furnaces should be equipped with adequate temperature controls because solder flow begins at approximately 45 to 50 °C (80 to 90 °F) above the solder liquidus. The optimum condition exists when the heating capacity of the furnace is sufficient to heat the parts rapidly to the liquidus of the solder.

Resistance soldering involves placing the workpiece either between a ground and a movable electrode or between two movable electrodes as part of an electrical circuit. Heat is applied to the joint both by the electrical resistance of the metal being soldered and by conduction from the electrode, which is usually carbon. Production assemblies can use multiple electrodes, rolling electrodes, or special electrodes, depending on which setup offers the most advantageous soldering speed, localized heating, and power consumption. Resistance soldering electrode bits generally cannot be tinned, and the solder must be fed directly into the joint.

Infrared Soldering. Optical soldering systems that focus infrared light (radiant energy) on the joint by means of a lens are available. Lamps with power ratings that range from 45 to 1500 W (140 to 4700 Btu/h) can be used for different application requirements. The devices can be programmed through a silicon-controlled rectifier (SCR) power supply with an internal timer. The most common sources of infrared heating for soldering applications are heated filaments. The quartz-iodine tungsten filament lamp is widely used because it is very stable and reliable over a wide range of temperatures. In general, infrared soldering systems are simple and inexpensive to operate. One of the most critical operating parameters is surface condition. Variations in the condition of the solder surface can be compensated for, to some extent, by adjusting the heating power. Advantages are process repeatability, ability to concentrate or focus the energy with reflectors and lenses, economy of operation, and absence of contact with the workpiece.

Ultrasonic soldering uses a transducer as the source of ultrasonic energy. The transducer is energized in a bath of molten solder, and sound waves are coupled between the transducer and the workpiece, allowing the oxides in the base metal to be disrupted so that the solder melts the base metal. Sound waves are transmitted throughout the base metal, permitting wetting to occur on surfaces that are "blind" to the source. Ultrasonic soldering is also used to apply solderable coatings on difficult-to-solder metals.

Hot gas soldering uses a fine jet of inert gas, heated to above the liquidus of the solder. The gas acts as a heat transfer medium and as a blanket to reduce access of air at the joint.

Spray gun soldering is a heating method used when the contour of the part to be soldered is difficult to follow with either a wiping or drop method or when the part is placed in the assembly in such a way that the solder cannot be applied after the parts are assembled. Gas-fired or electrically heated guns are available. Each type is designed to spray molten or semimolten solder on the work from a continuously fed solid solder wire. Soldering guns use either propane mixed with oxygen or natural gas mixed with air to heat and to spray a continuously fed solid solder wire of approximately 3.2 mm (0.12 in.) diameter.

About 90% of the solder wire is melted by the flame of the gun. The solder contacts the workpiece in a semiliquid form. The workpiece then supplies the balance of the heat required to melt and flow the solder. Adjustments can be made within the spray gun to control the solder spray.

Vapor-phase soldering (also known as condensation soldering) uses the latent heat of vaporization of a condensing saturated liquid to provide the heat required for soldering. A reservoir of saturated vapor over a boiling liquid provides a constant controlled temperature with rapid heat transfer. This method is useful for large assemblies, as well as for temperature-sensitive parts.

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CHAPTER 8

Mechanical Fastening

THE PRIMARY FUNCTION of a fastener system is to transfer load. Many types of fasteners and fastening systems have been developed for specific requirements, such as high strength, easy maintenance, corrosion resistance, reliability at high or low temperatures, or low material and manufacturing costs. Important structural fasteners include bolts and nuts, screws, pin and collar fasteners, rivets, and blind fasteners (Fig. 8.1). However, many other types of fasteners are designed for common and specialty applications. The selection and satisfactory use of a particular fastener are dictated by the design requirements and conditions under which the fastener will be used. Important considerations include the purpose of the fastener, the type and thickness of materials to be joined, the configuration and total thickness of the joint to be fastened, the operating environment, and the type of loading to which the fastener will be subjected in service. A careful analysis of these requirements is necessary before a satisfactory fastener can be selected.

The selection of the correct fastener or fastener system may simply involve satisfying a requirement for strength (static or fatigue) or for corrosion resistance. On the other hand, selection may be dictated by a complex system of specification and qualification controls. The extent and complexity of the system needed are usually dictated by the probable cost of a fastener failure. Adequate testing is the safest method of guarding against failure of a new fastener system for a critical application. The designer must not extrapolate existing data to a different size of the same fastener, because larger-diameter fasteners have significantly lower fatigue endurance limits than do smaller-diameter fasteners made from the same material using the same manufacturing techniques and joint system.

The advantages of mechanical fastening include:

- Mechanical fastening is a straightforward and lower-risk joining process. It can often be accomplished with semiskilled workers. In addition, no stringent surface preparations are required.

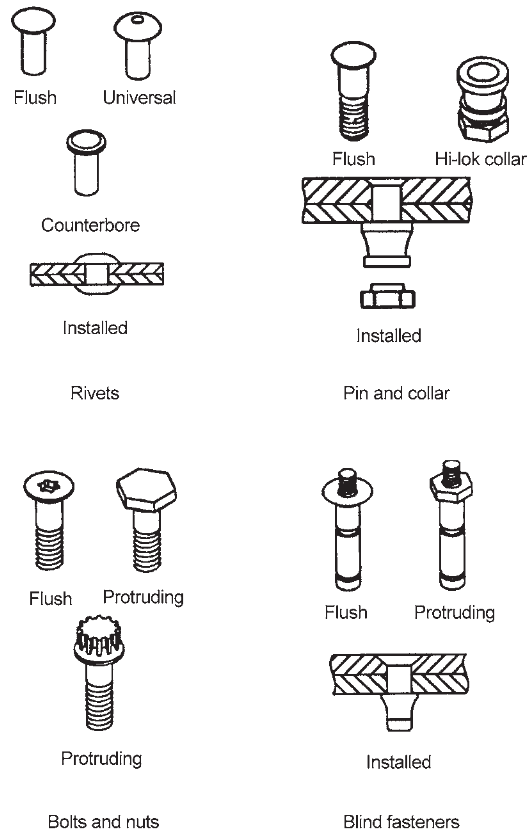


Fig. 8.1 Typical structural fasteners. Source: Ref 8.1

- Compared with adhesive bonding, mechanical fastening provides better through-the-thickness reinforcement and is not as sensitive to peel stresses or residual stress affects.
- Mechanically fastened joints do not normally require nondestructive testing.
- Many mechanically fastened joints allow disassembly or panel removal. Some fasteners are designed for permanent installation, whereas others allow easy removal.
- Mechanically fastened joints are very amenable to field repairs since the installation process is straightforward and the tools are relatively simple.

The disadvantages of mechanical fastening include:

- Relatively low joint efficiencies are obtained. Due to the stress concentration caused by the presence of holes, fatigue properties are reduced.

- Obtaining and maintaining proper preload (torque) on an installed fastener can be problematic.
- Some high-performance fasteners are expensive.
- Improper hole preparation procedures and poor shimming practices can induce residual stresses during assembly.
- Fretting and corrosion of the joints during service can be a problem.

8.1 Mechanically Fastened Joints

A simple single fastener single-lap shear joint is shown in Fig. 8.2. The key dimensions are:

- *d*, fastener diameter
- *t*, thickness of the joint elements
- *w*, width of the plate
- *e*, edge distance
- *P*, load
- *dt*, bearing area loaded in compression
- *2et*, total shear-out area loaded in shear
- $(w - d)/t$, net section loaded in tension
- *wt*, gross section loaded in tension

The average stresses in the joint are:

Average bearing stress $\sigma_b = P/dt$ (Eq 8.1)

Average shear-out stress $\sigma_{so} = P/2et$ (Eq 8.2)

Average set section stress $\sigma_n = P/(w - d)t$ (Eq 8.3)

Average gross section stress $\sigma_g = P/wt$ (Eq 8.4)

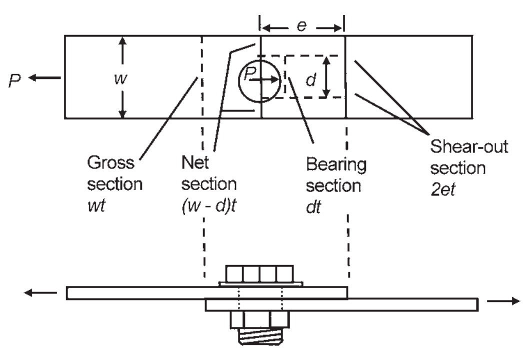


Fig. 8.2 Single-shear joint. Source: Ref 8.2

When doing a joint analysis, it is necessary to calculate the failing stress for each of these conditions. Failure will occur at the condition with the lowest joint strength.

Fasteners can be loaded in pure tension, pure shear, or, more commonly, a combination of both. The typical stresses in a bolted joint are shown in Fig. 8.3. If the design is predominantly tension, both the head and nut should be strong enough to take a high torque and subsequent high tension loads without yielding. If the bolt goes into a tapped hole, the hole must have enough thread engagement to develop the full bolt load without yielding. If the threaded material is too weak to take the load, it may be necessary to first install a threaded insert.

If the dominant load is shear, then the thickness of the joint sheet/plate material should be critical in bearing to allow for proper load distribution. Otherwise, some bolts can fail before others load up, due to tolerances on clearance hole locations and diameters. Bolts should not have threads in shear, so the grip lengths (unthreaded shank lengths) should be selected such that a flat washer under the nut will allow tightening and still have smooth shank in the hole.

Two different joint configurations are shown in Fig. 8.4. While the fasteners in both configurations are loaded in shear, the double-shear joint (Fig. 8.4b) is the much preferred. Single-shear joints (Fig. 8.4a) cause problems due to the eccentric load path causing fastener rotation (Fig. 8.5). Fastener cocking during loading can result in point loading and lead to progressive damage during fatigue cycling. Therefore, double-shear joints are much preferred if at all possible.

8.1.1 Fastener Preload

The primary force on an unloaded but an installed bolt is tension, which is set up by stretching the bolt during tightening, whereas the most important stress in the nut is the shear stress in the threads. The bolt behaves like a spring (Fig. 8.6a). When the bolt is preloaded or when the spring is stretched, a stress is induced in the bolt and a clamping force is induced in the structure before any working load is encountered. As the working load

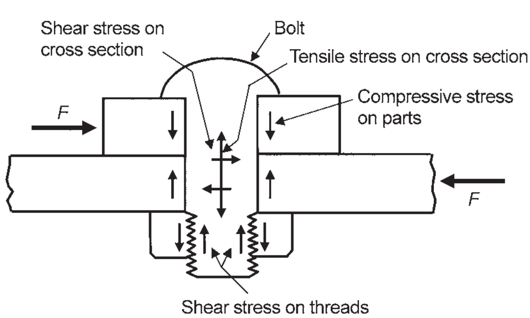
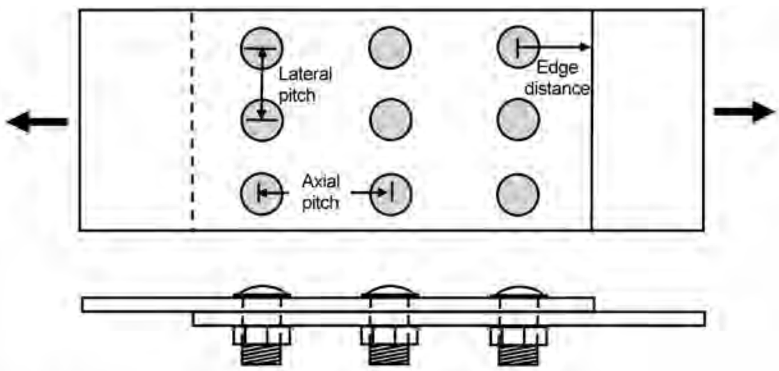
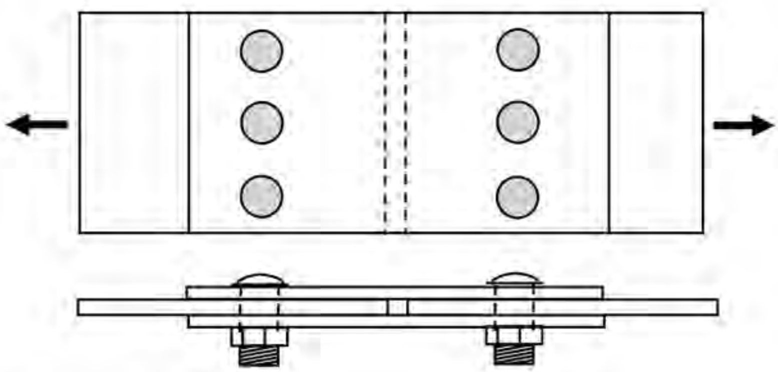


Fig. 8.3 Typical stresses in a bolted joint



(a) Multifastener single-shear joint



(b) Multifastener single-shear butt joint

Fig. 8.4 Typical mechanical fastened joints

is applied, the preloaded bolt does not encounter an additional load until the working load equals the preload in the bolt (Fig. 8.6b). At this point, the force between members is zero. As more load is applied, the bolt must stretch. Only beyond this point will any cyclic working load be transmitted to the bolt. When the bolt encounters an increase in load, being elastic, it stretches. If this stretch (strain) exceeds the elastic limit, the bolt yields plastically, taking a permanent set. The result is a loss in preload or clamping force (dashed curve, Fig. 8.6c). With a fluctuating load, this situation can cycle progressively, with continued loss of preload and possibly rapid fatigue failure.

To eliminate fatigue problems that occur at room temperature, the designer should specify as high an initial preload as practical. The optimum fastener torque values for applying specific loads to the joint have been determined for many high-strength fasteners. However, these values should be used with caution, because the tension produced by a selected torque

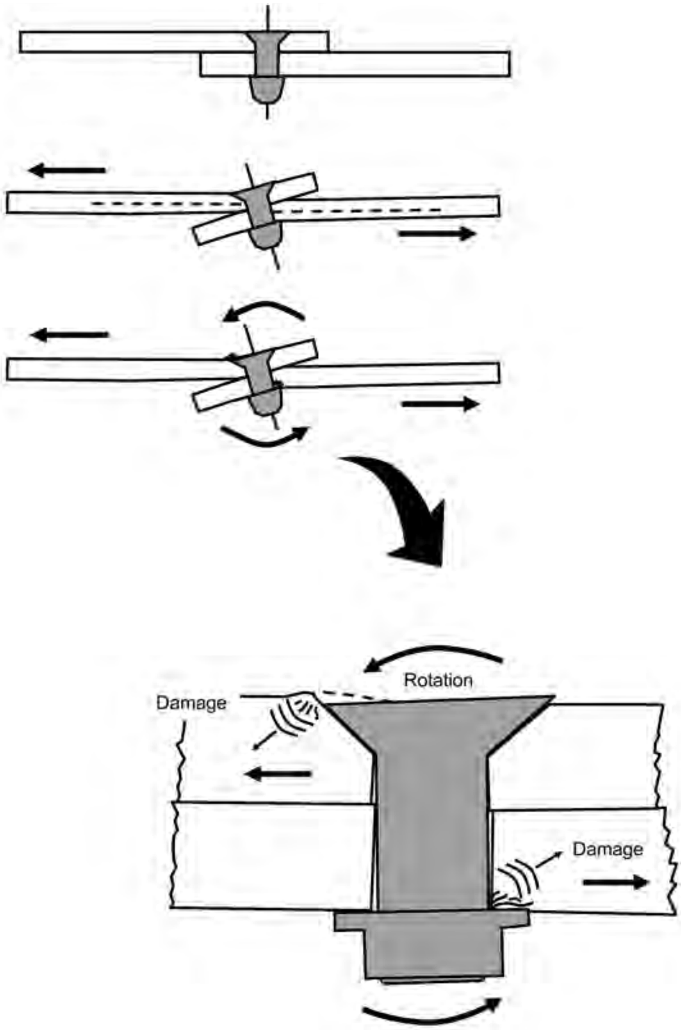


Fig. 8.5 Fastener cocking in single-lap shear. Source: Ref 8.2

value depends directly on the friction between the contacting threads. With the proper selection of materials, proper design of bolt-and-nut bearing surfaces, and the use of locking devices, the assumption is that the initial clamping force will be sustained during the life of the fastened joint. This assumption cannot be made in elevated-temperature design.

At elevated temperature, the induced bolt load will decrease with time as a result of creep, even if the elastic limits of the materials are not exceeded, and this can adversely affect fastener performance. Therefore, it is necessary to compensate for high-temperature conditions in advance when assembling the joint at room temperature. Failures that occur at elevated temperatures necessitate evaluation of the properties of the fastener mate-

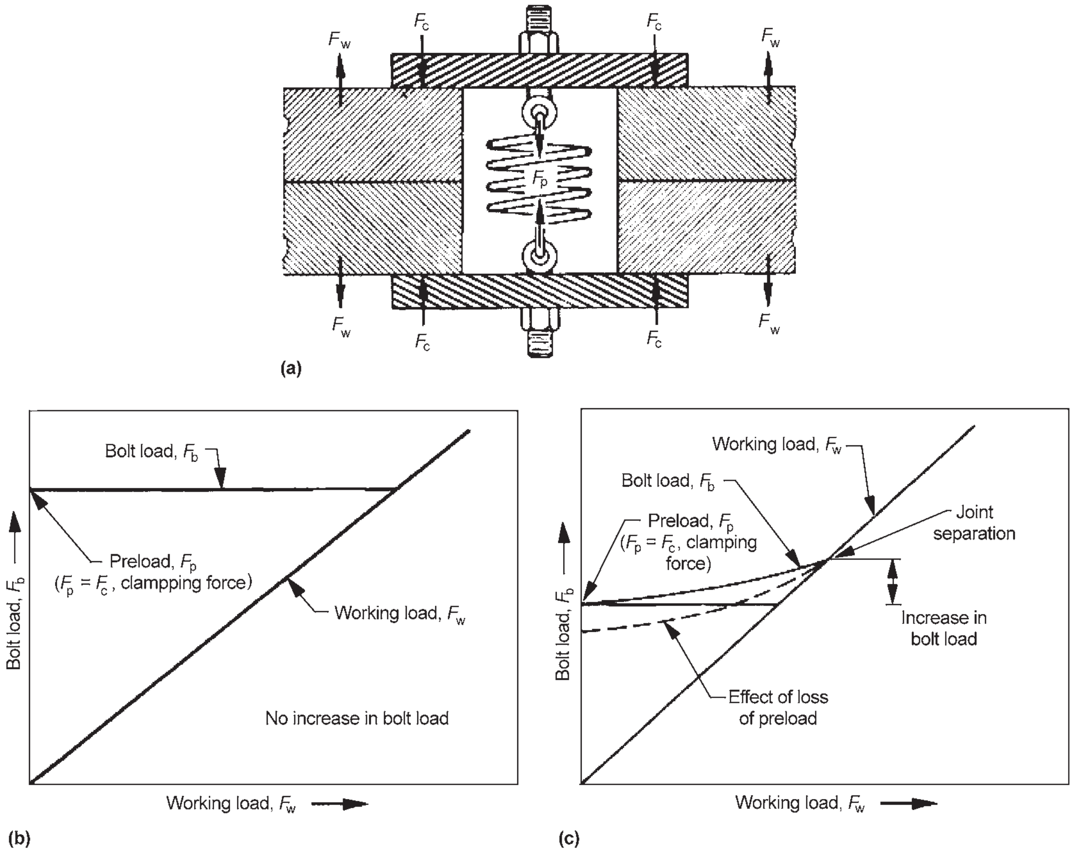


Fig. 8.6 Springlike effect of loading conditions on bolted joints: (a) theoretical load condition for an elastic fastener and a rigid structure, (b) ideal relationship of bolt load to working load with an elastic fastener and a rigid structure, and (c) actual relationship (both fastener and structure elastic) of bolt load to working load. Source: Ref 8.3

rial relative to the applied loads, operating temperature, and time under load at temperature.

The amount of clamping force that the fastener must provide to hold the assembly together must be sufficient to both maintain preloading and prevent slipping of the parts or opening of the joint when service loads are applied. The factors that primarily establish the preload requirement are the stiffness of the materials in the joint and the loads that are placed on the assembly.

Fastener tension can be measured using different devices, such as strain-gaged bolts or fastener force washers, or by using special techniques, such as ultrasonic bolt measurement. Although these devices and methods are useful for research, they are often impractical or costly for evaluating fastener tension in production quality control efforts. The most common method to indirectly estimate fastener tension is: (a) taking torque measurements as the fastener is tightened or (b) using a fastener that has a nut that breaks away at a predetermined torque during installation. The fastener shown in Fig. 8.7 contains a nut with a breakaway groove, which controls the amount of torque and preload on the pin. The nut is tightened down until a predetermined torque level is achieved, and the top portion of the nut fractures.

Using torque as a measure of preload assumes that the relationship between torque and tension is known, such that, for example, the nut factor, K, from the simple equation $T = KDF$ (where T is torque, D is diameter, and F is clamping force) is established and known to have acceptable variability. However, for tension to be developed, the torque applied to a fastener must overcome friction under the head of the fastener and in the threads, and the fastener or nut must turn. Because friction can absorb as much as 90 to 95% of the energy applied to the fastener, as little as 5 to 10% of the energy is left for generating fastener tension (Fig. 8.8). If the amount of friction varies greatly, wide variations in clamping force are produced, which can mean loose or broken bolts, leading to assembly failures.

Therefore, if torque alone is measured, it can never be known with certainty whether the desired tension has been achieved. Thus, unfortunately, torque is a highly unreliable, totally inaccurate measurement for evaluation of the preload on a threaded fastener. For many noncritical fasteners, where safety or the functional performance of an assembly is not compromised, it may be acceptable to specify and monitor torque alone. The most common measurement tools are hand torque wrenches that are used for installation and torque audit measurements and rotary torque sensors that

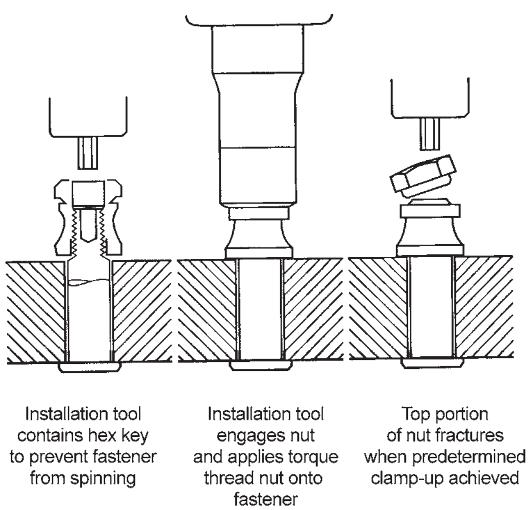


Fig. 8.7 Installation of fastener with breakaway nut to control clamp-up. Source: Ref 8.1

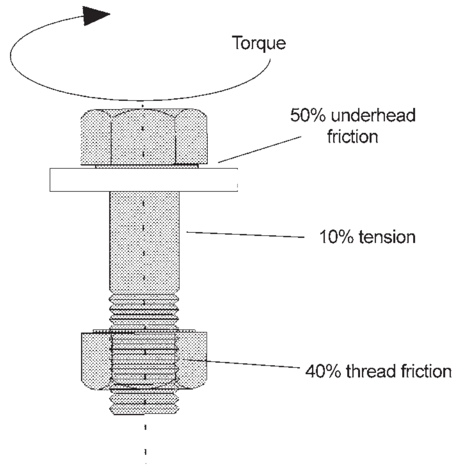


Fig. 8.8 Typical distribution of energy from torque applied to a bolted assembly. Source: Ref 8.4

are used to measure installation torque dynamically. To ensure proper assembly of critical fasteners, more than torque must be measured.

8.1.2 Preload Control

Insufficient preload, caused by an inaccurate tightening method, is a frequent cause of bolted joint failure. Six main methods are used to control the preload of a threaded fastener:

- *Torque control tightening:* Controlling the torque on a fastener is the most popular means of controlling preload. The nominal torque necessary to tighten the bolt to a given preload can be determined either from tables or by calculation using a relationship between torque and the resulting bolt tension. A fundamental problem with torque tightening is that because most of the torque is used to overcome friction, slight variations in the frictional conditions can lead to large changes in the bolt preload.
- *Angle-controlled tightening:* This method, also known as turn-of-the-nut method, has been applied to power wrenches, the bolt being tightened to a predetermined angle beyond the elastic range, and results in a small variation in the preload, due in part to the yield stress tolerance. The main disadvantages of this method lie in the necessity for precise and, if possible, experimental determination of the angle. In addition, the fastener can sustain only a limited number of retorques before it fails.
- *Yield-controlled tightening:* An electronic control system is used that is sensitive to the torque gradient of the bolt being tightened. Rapid detection of the change in slope of this gradient indicates the yield

point has been reached and stops the tightening process. This is achieved by incorporating sensors to read torque and angle during the tightening process. Since angle of rotation and torque are both measured by the control system, permissible values can be used to detect fasteners that lie outside their specification (e.g., having too low a yield). A small degree of preload scatter still results from this method due to the influence of friction. The method detects the yield point of the fastener under the action of combined tension and torsion. The higher the thread friction, the higher the torsional stress, which for a given yield value results in a lower preload due to a lower direct stress. Because of the cost of the tools necessary to use this method, widespread adoption of this method is unlikely.

- *Bolt stretch method:* The method uses a small hydraulic ram that fits over the nut; the threaded portion of the bolt/stud protrudes well past the nut, and a threaded puller is attached. Hydraulic oil from a small pump acts upon the hydraulic ram, which in turn acts upon the puller. This force is transmitted to the bolt, resulting in extension. The nut can then be rotated by hand. Control of the hydraulic pressure effectively controls the preload in the bolt.
- *Heat tightening:* This method uses the thermal expansion characteristics of the bolt. The bolt is heated and expands, the nut is indexed using the angle of turn method, and the system is then allowed to cool. As the bolt attempts to contract, it is constrained longitudinally by the clamped material, and a preload results. The process is slow and not widely used. It is generally used only on very large bolts.
- *Tension indicating methods:* This method category includes the use of special load-indicating bolts, load-indicating washers, and methods that determine the length change of the fastener. Bolt tension can be indirectly measured a wide number of ways. Special bolts have been designed that indicate the force in the bolt.

Whatever method is used to tighten a bolt, a degree of bolt preload scatter is to be expected.

The key to preventing self-loosening of fasteners is to ensure that sufficient clamp force is present on the joint interface to prevent relative motion between the bolt head or nut and the joint; the joint is designed to allow for the effects of any plastic deformation and stress relaxation, and proven thread-locking devices are specified. A multitude of thread locking devices are available. Through the efforts of American National Standards Subcommittee B18:2 on locking fasteners, three basic locking fastener categories have been established:

Free Spinning. The free-spinning type is a plain bolt with a circumferential row of teeth under the washer head. It is ramped, allowing the bolt to rotate in the clamping direction but to lock into the bearing surface when rotated in the loosening direction.

Friction Locking. Friction locking categories can be subdivided into two groupings, metallic and nonmetallic. The metallic friction-locking fastener usually has a distorted thread that provides the desired torque. Nonmetallic friction locking devices have plastic inserts (e.g., nylon) that provide a thread-locking function.

Chemical Locking. These are adhesives that fill the gaps between the male and female threads and bond them together. Such adhesives are now available in microencapsulated form and can be preapplied to the thread. When the fastener is engaged with its mating thread, the capsules are crushed, and the shearing action of the rotating fastener mixes the epoxy and hardener, initiating the adhesive cure.

8.2 Fastener Selection

The selection of a specific fastener depends on its ability to satisfactorily transmit the expected design loads, to be environmentally compatible with the materials it joins, and to be amenable to installation in the intended joint. Environmental or corrosion compatibility depends on both the fastener material and the materials in the joint. Fasteners, especially steel fasteners, are often coated for corrosion protection (e.g., cadmium), and the compatibility of the coating with materials being joined needs to be considered. For example, cadmium-plated fasteners should not be used with titanium because of the potential of stress corrosion cracking.

8.2.1 Fastener Materials

Fasteners can be made from many materials, but most are made from carbon steel, alloy steel, or stainless steel. Stainless steels include both iron- and nickel-based chromium alloys. Copper-based alloys of brass and bronze are often used for decorative applications or in applications where rusting is undesirable. Titanium fasteners have limited usage, primarily in the aerospace industry.

Carbon and Alloy Steel. Steel is the most commonly used material in fastener production, constituting nearly 90% of all fasteners manufactured annually. This metal's popularity stems from its high degree of formability coupled with tensile strength and durability. Compared with other metal stock, steel is also relatively inexpensive to fabricate. It is frequently processed with zinc or chrome plating but can also be formed without any surface treatments. Typically, their ultimate tensile strength is 380 MPa (55 ksi). An alloy steel is a high-strength steel that can be heat treated to a tensile strength of 2068 MPa (300 ksi). However, it is not corrosion resistant and must therefore have some type of coating to protect it. Aerospace alloy steel fasteners are usually cadmium plated for corrosion protection. Carbon and alloy steel become embrittled at temperatures <–54 °C (<–65 °F).

Carbon steel is the most common type of steel used in fastener production. Grades 2, 5, and 8 are typically the standard for carbon-steel-based screws and bolts, with alloyed carbon steel being a higher-end variation on these metals. Material properties for these grades include:

- *Grade 2:* This is a low-carbon category that features the least expensive, but also least durable, types of steel. Grade 2 material is highly workable and forms the bulk of steel-grade fasteners.
- *Grade 5:* Grade 5 steels are produced from unalloyed medium-carbon groups, such as type 1038, and are usually work hardened to improve their strength. This is the most common grade used in automotive applications.
- *Grade 8:* These steels are typically medium carbon alloys, such as types 4037 and 4340. They are work hardened to a high degree, making them stronger and better suited for mechanically straining applications, such as vehicle suspension systems.
- *Alloy steel:* This is an alloy formed with high-strength carbon steel that can be thermally treated up to 2068 MPa (300 ksi). Alloy steel has low corrosion resistance and typically benefits from additional coating. These steels are extremely strong but can be subject to hydrogen embrittlement and stress corrosion cracking.

Stainless Steel. Stainless steel fasteners are available in a variety alloys with ultimate strengths ranging from 480 to 1520 MPa (70 to 220 ksi). The major advantages of stainless steel are that it normally does not require a protective coating for corrosion resistance and that it has a wider service temperature range than plain carbon or alloy steels. Series 400 stainless steels contain only 12% chromium and will corrode in certain environments.

Stainless steels are generally stronger than most grade 2 steels but weaker than many hardened grade 5 and 8 varieties. Stainless steel fasteners are less magnetic than their standard steel counterparts. The two main categories of stainless steel fastener materials are:

- *Austenitic stainless steel:* The vast majority of stainless steel fasteners are produced with metals from the austenitic family. Their high levels of chromium and nickel provide tough corrosion resistance and the ability to withstand considerable physical strain without fracturing, albeit at a higher cost than the martensitic varieties.
- *Martensitic stainless steel:* The martensitic group includes strong, durable stainless steels that can be further strengthened through heat treatment. They are more magnetic than other types of steel but have lower corrosion resistance.

Copper-Based Alloys. The bronze used in fastener production is an alloy primarily consisting of tin and copper. With its high corrosion resistance, bronze is well suited for aquatic applications, such as shipbuilding or underwater construction. It shares copper's reddish color but is relatively expensive compared with other fastener materials. Brass, an alloy of copper and zinc, is similar to bronze in its anticorrosive and electric conductivity properties, but it has lower tensile strength and is a relatively soft metal. Part of brass's appeal as a fabricating material lies in its yellowish golden color. Brass and bronze fasteners have only moderate strength but do not rust like some steel fasteners. Available brass and bronze alloys include naval brass (60% Cu-40% Zn), aluminum bronze, phosphor bronze, silicon bronze, nickel-copper alloys, and nickel-copper-aluminum alloys.

Aerospace fasteners. Titanium (Ti-6Al-4V) is widely used in the aerospace industry as a result of its high strength-to-weight ratio and corrosion resistance. When higher strength is required, cold-worked A286 iron-nickel or the iron-nickel-based alloy Inconel 718 can be used. If extremely high strengths are required for very highly loaded joints, the nickel-cobalt-chromium multiphase alloys MP35N and MP159 are available.

Nylon Fasteners. Nylon is a lightweight synthetic plastic material used for specific fastener applications. It is corrosion resistant, has high electrical and thermal insulating properties, and can be easily dyed to meet aesthetic requirements, such as those necessary for fastener replacement. However, nylon is subject to severe deterioration under elevated temperatures and may become weakened in low-temperature environments. In addition, its comparatively low strength does not allow its use in load-bearing applications.

8.2.2 Corrosion Protection

Corrosion is electrochemical in nature; therefore, an electrolyte must be present. Water is an excellent electrolyte, especially if it contains dissolved minerals. Temperature is also important because little reaction occurs <5 °C (<40 °F). Oxygen is required and is present in the atmosphere and, to a lesser extent, underwater and underground. Types of corrosion include atmospheric corrosion, liquid-immersion corrosion, crevice corrosion, galvanic corrosion, stress-corrosion cracking, and hydrogen damage.

When dissimilar metals are in contact or are electrically connected together, galvanic corrosion results because of the electrical potential existing between the two metals. The current produced has a great effect on metal corrosion and must be considered whenever different metals are to be fastened together. Galvanic corrosion should be kept in mind at all times when designing structures using fasteners. For a structure to be well designed, the anode or corroding-metal area should be large relative to the cathode or protected metal in order to ensure reasonable anode life. With fasteners, this is sometimes difficult to accomplish because fasteners are always smaller than the structure they join. In one example of the size effect, iron nails were once used to fasten copper sheathing to the bottom of wooden ships to prevent marine growth. At the end of each voyage, most of this sheathing had fallen off because of the accelerated corrosion of the iron nails. Galvanic corrosion can be avoided by using the same metal for both fastener and structure. Several alternatives exist when this is impractical or impossible: the structure may be painted, the fastener may be isolated by nonconducting materials or plated with a more noble metal, moisture may be prevented from contacting the couple, or fasteners may be made of a metal that will be protected by sacrificial corrosion of the much larger mass of the metal being fastened.

The most commonly used protective metal coatings for steel fasteners are zinc, cadmium, and aluminum. Tin, lead, copper, nickel, and chromium are also used, but only to a minor extent and for very special applications. In many cases, however, fasteners are protected by some means other than metallic coatings. They are sometimes sheltered from moisture or covered with a material that prevents moisture from making contact, thus drastically reducing or eliminating corrosion. For fasteners exposed to the elements, painting is universally used.

Zinc Coating. Zinc is the coating material most widely used for protection of steel fasteners from corrosion. The hot dip method of zinc plating is known commercially as galvanizing. Zinc can also be electrodeposited. Because zinc plating has a dull appearance, it is less pleasing in appearance than cadmium. Zinc is a sacrificial material. It will migrate to uncoated areas that has its plating scratched off, thus continuing to provide corrosion resistance. Zinc may also be as a zinc-rich paint. Zinc melts at 420 °C (785 °F) but has a useful service temperature limit to 120 °C (250 °F), although its corrosion inhibiting qualities start degrading above 60 °C (140 °F).

Cadmium Plating. Cadmium coatings are also applied to steel fasteners by an electroplating process similar to that used for zinc. As is true for zinc, cadmium corrosion life is proportional to the coating thickness. The main advantage of cadmium over zinc is in marine environments, where the corrosion life of cadmium is longer. Cadmium-plated steel fasteners also are used in aircraft in contact with aluminum because the galvanic characteristics of cadmium are more favorable than those of zinc. Cadmium-plated fasteners must be baked at 190 °C (375 °F) for 23 h within 2 h after plating to prevent hydrogen embrittlement. Since cadmium melts at 315 °C (600 °F), its useful service temperature limit is 230 °C (450 °F).

Phosphate Coating. Steel fasteners are coated in a solution of phosphoric acid by submerging the fastener in a proprietary bath. The chemical reaction forms a mildly protective layer of crystalline phosphate. The three principal types of phosphate coatings are zinc, iron, and manganese. Phosphate-coated parts can be readily painted, or they can be dipped in oil or wax to improve the corrosion resistance. Fasteners are usually phosphated with either zinc or manganese. Phosphate coatings start deteriorating at 107 °C (225 °F) for heavy zinc to 205 °C (400 °F) for iron phosphate.

Passivation of Stainless Steel Fasteners. Stainless steel fasteners can cause galvanic corrosion or oxidation in a joint unless they are passivated or preoxidized before assembly. Passivation is the formation of a protective oxide coating on the steel by treating briefly with an acid. The oxide coating is almost inert. Preoxidation is conducted by exposing the fasteners to approximately 55 °C (130 °F) in an air furnace. The surface formed is inert enough to prevent galling due to galvanic corrosion.

Chromium Plating. Chromium plating is commonly used for automotive and appliance decorative applications, but it is not common for fasteners. Chromium-plated steel fasteners cost approximately as much as stainless steel fasteners. An adherent chromium plating requires both copper and nickel plating before chromium plating. Chromium plating also has hydrogen embrittlement problems. However, it is acceptable for maximum operating temperatures of 425 to 650 °C (800 to 1200 °F).

Aluminum Coating. Aluminum coatings on fasteners offer the best protection of all coatings against atmospheric corrosion. Aluminum coatings also give excellent corrosion protection in seawater immersion and in high-temperature applications. Aluminum coatings are applied by hot dip methods at about 675 to 705 °C (1250 to 1300 °F). Aluminum alloy 1100 is usually used because of its general all-around corrosion resistance. Aluminum coatings will protect steel from scaling at temperatures up to about 540 °C (1000 °F); the aluminum coating remains substantially the same as when applied, and its life is exceptionally long. Prevention of galling at elevated temperatures is another characteristic of aluminum coatings. Stainless steel fasteners for use at 650 °C (1200 °F) have been aluminum coated just to prevent galling. Coated nuts can be removed with an ordinary wrench after many hours at these temperatures, which is impossible with uncoated nuts.

8.2.3 Thread Fundamentals

Threaded fasteners (screws, bolts, nuts, machine screws, cap screws, set screws, and drive screws) are used to provide a clamping force between two or more parts and where there is likely to be a need for dismantling at some time in the future, whether for access or for maintenance. The thread can be described as an inclined plane wrapped around a cylinder. External threads are those on bolts, studs, or screws. Internal threads are threads on nuts and tapped holes. The configuration of the thread (Fig. 8.9) in an axial plane is the thread form, or profile, and the three parts making the form are the crest, root, and flank. An intentional clearance is created between mating threads known as the allowance. This ensures that when both the internal and external threads are manufactured there will be a positive space between them. For fasteners, the allowance is generally

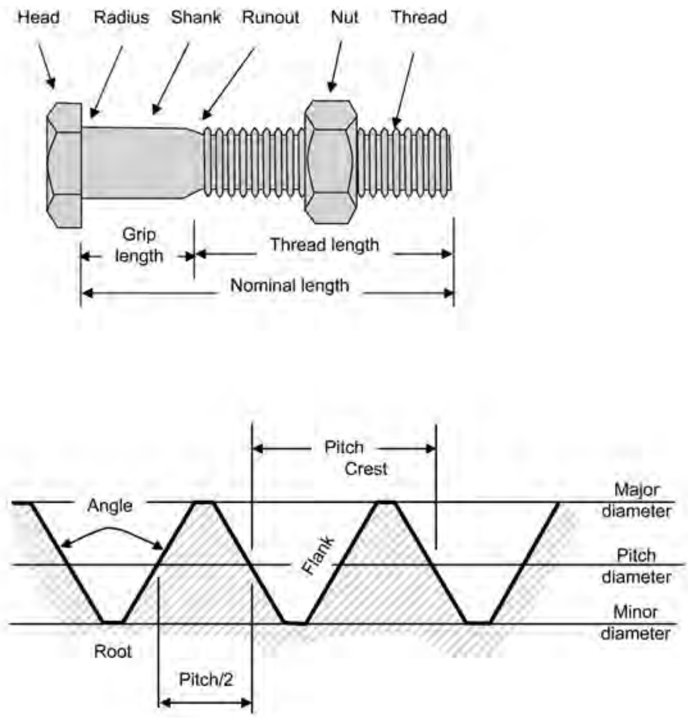


Fig. 8.9 Bolt and thread nomenclature

applied to the external thread. Tolerances are specified amounts by which dimensions are permitted to vary for convenience of manufacturing. The tolerance is the difference between the maximum and minimum permitted limits.

Thread Fit. Thread fit is the combination of allowances and tolerances and is a measure of tightness or looseness between them. A clearance fit is one that provides a free-running assembly and an interference fit is one having specified limits of thread size that always result in a positive interference between the threads when assembled. Unified inch screw threads have six classes of fit: 1B, 2B, and 3B for internal threads and 1A, 2A, and 3A for external threads. All are considered clearance fits. This means they assemble without interference. The higher the class number, the tighter the fit. The A designates an external thread, and the B designates an internal thread.

- *Classes 1A and 1B* are considered an extremely loose-tolerance thread fit. This class is suited for quick and easy assembly and disassembly. For mechanical fasteners, this thread fit is rarely specified.
- *Classes 2A and 2B* offer optimum thread fit that balances fastener performance, manufacturing economy, and convenience. Nearly 90% of all commercial and industrial fasteners produced in North America have this class of thread fit.

- *Classes 3A and 3B* are suited for close-tolerance fasteners. These fasteners are intended for service where safety is a critical design consideration. This class of fit has restrictive tolerances and no allowance.

The axial distance through which the fully formed threads of both the internal and external threads are in contact is known as the length of thread engagement. The depth of thread engagement is the distance the threads overlap in a radial direction. The length of thread engagement is one of the key strength aspects that the designer may be able to control.

Thread Series. Three standard thread series in the unified screw thread system are highly important for fasteners: UNC (coarse), UNF (fine), and 8-UN (8-thread). The advantages of using a fine thread are that because they have larger stress areas, they are stronger in tension, their larger minor diameters develop higher torsional and transverse shear strength, they can tap better in thin-walled members, and with their smaller helix angle they permit closer adjustment accuracy. Coarse threads exhibit stripping strengths that are greater for the same length of engagement, exhibit a better fatigue resistance behavior, have less tendency to cross thread, assemble and disassemble more quickly and easily, tap better into brittle materials, and have larger thread allowances that allow for thicker coatings and plating. With the increase in automated assembly processes, the use of the coarse thread series has expanded.

Thread Strength. Two fundamentals must be considered when designing a threaded connection: (a) ensure that these threaded fasteners were manufactured to some current ASTM, ANSI, U.S. government, or other trusted standard, and (b) design bolts to break in tension before the female and/or male threads strip. A broken bolt is an obvious failure because it is loose. However, when the threads strip before the bolt breaks, the failure may not be discovered until after the fastener is put into service.

Thread Production. There are basically two methods of producing threads, cut and rolled. The shank on a blank that is to be a cut thread will be full size from the fillet under the head to the end of the bolt. Thread cutting involves removing the material from a bolt blank to produce the thread with a cutting die or lathe. By doing this, the grain flow of the material is interrupted. Cold-rolled threads are formed by rolling a reduced-diameter portion of the shank between dies. On external threads, the dies apply pressure, compressing the material, forming the minor diameter, and allowing the material to expand to form the major diameter. Rolling of the thread has several advantages: more accurate and uniform thread dimension, smoother thread surface, and generally greater thread strength, particularly fatigue and shear strength.

8.2.4 Fastener Specifications

Specifications are used to outline fastener requirements, to control the manufacturing process, and to establish functional or performance standards. Their goal is to ensure that fasteners will be interchangeable, dimensionally and functionally. The most common fastener specifications are product specifications that are set up to govern and define the quality and reliability of fasteners before they leave the manufacturer. These specifications determine what material to use; state the objectives for tensile strength, shear strength, and response to heat treatment; set requirements for environmental temperature or atmospheric exposure; and define methods for testing and evaluation. To ensure proper use of fasteners, additional specifications are necessary as a guide to proper design application and installation. All ASTM and SAE specifications covering threaded fasteners require that the heads be marked for grade identification. Grade markings are a safety device that provides a positive check on selection, use, and inspection. The markings reduce the possibility of selecting and using a bolt of insufficient strength, which might lead to a failure and cause damage to equipment or injury of personnel.

8.3 Structural Bolts and Screws

Bolts, along with nuts and washers, and screws (Fig. 8.10) are used to join structural members that must be removable for service access. They are also used as permanent attachments for structure. Structural bolts and screws are used in fatigue, shear, and tension critical joints. Nuts, which are tightened with wrenches, may be used when there is access to both sides. Nut plates and gang channels are used when one-sided access is applicable. The shanks of all structural bolts must be long enough to ensure that there are no threads in the joint that will bear or dig into the sides of the hole. Extra washers may be used to adjust the grip length. However, the use of lock washers is often prohibited because they can damage the protective finish on the structure being joined. A washer should be used under both the bolt head of protruding bolts and the nut to help distribute the load and prevent damaging the surface finish.

There are many head styles (Fig. 8.11), including protruding tension flange head, protruding shear head, 100° full countersink, and 100° reduced countersink. For structural bolts and screws, the threads are rolled

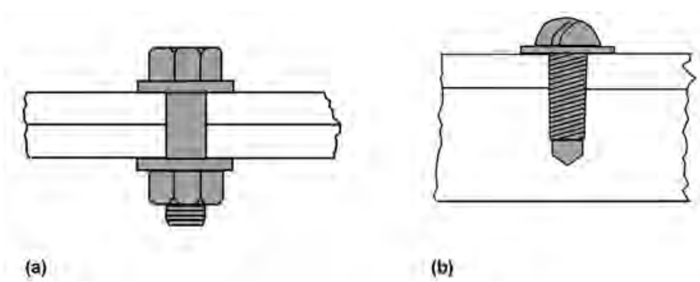


Fig. 8.10 Typical assemblies using (a) a bolt and nut and (b) a screw

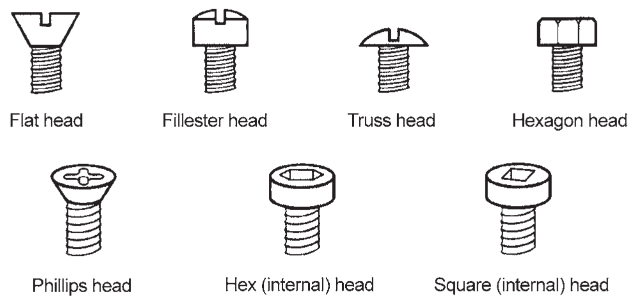


Fig. 8.11 Typical head forms for bolts and screws. Source: Ref 8.5,

and the heads are forged for additional strength. Since both of these operations induce residual compression stresses in the fastener, they also improve their resistance to stress corrosion cracking. Bolts <5 mm (<0.19 in.) in diameter are considered to be nonstructural; they are used to attach brackets and other miscellaneous hardware. The threads on nonstructural bolts and screws can be either machined or rolled. Some nuts are self-locking, while others are not. Cotter pins or safety wire are used to secure those without self-locking features. Self-aligning nuts (up to 8°) are available for situations in which the structural members are not parallel. There are also nuts designed specifically for tension- or shear-loading applications.

When installing structural bolts, a high preload (i.e., high torque) is desirable from the standpoint of fatigue and vibration. However, since a high preload places the bolt under tension stress, too high a preload can increase the susceptibility of certain fastener materials to stress corrosion cracking. Therefore, bolt preload is usually restricted to around 50 to 60% of the bolt yield strength. It is also important that all of the fasteners in the joint are preloaded to close to the same torque, so that the fasteners share the load equally. If there is variable torque on the fasteners, those that are preloaded to higher values will carry a substantially higher portion of the load than those with lower preload. Low bolt preloads can result in joint rotation, misalignment, loosening, and the formation of gaps between mating parts. Low bolt preloads also reduce the fatigue life of the installed fastener. For highly loaded bolted joints, torque values are often specified on the engineering drawing. Where screws are used in tapped holes, a failure under tension loads should be by breakage at the core of the bolt thread rather than by stripping of the thread. Where bolts are in shear, designers should ensure that the loads are carried on the bolt shank rather than on the threaded portion.

Locknuts. A locknut is a device that provides extra resistance to vibration loosening beyond that produced by proper preload, either by providing some form of prevailing torque or, in free-spinning locknuts, by deforming, crimping, or biting into mating parts when fully tightened. A locknut counters the back-off torque created by the inclined planes of the thread. Locknuts and locking mechanisms take many forms (Fig. 8.12), such as thread interference locknuts, also known as prevailing torque locknuts that use several different forms, nuts with out-of-round holes, a nylon locking collar in the nut, a nylon patch, or mechanically deformed dimples or crimps. Another form of locking devices is the free-spinning locknut, such as springhead nuts, beam-type nuts, and serrated nut bearing surfaces.

Washers. Washers are used to provide a seating for nuts and bolts to distribute the load over an area greater than that provided by the bolt head or nut. It also prevents damage to the surfaces being joined due to rotation of the nut or bolt. Washers can also seal, cover oversize holes, and act as a spring take-up between fastener and work piece. Some also have the special task of preventing unwanted rotation of the nut or bolt, such as spring washers and serrated-tooth types. A variety of different washer types are illustrated in Fig. 8.13. Joints that use either bolts or screws should have washers because:

- *Bearing stress:* Using washers reduces the bearing stress on the member surfaces by distributing the load over the washer area instead of

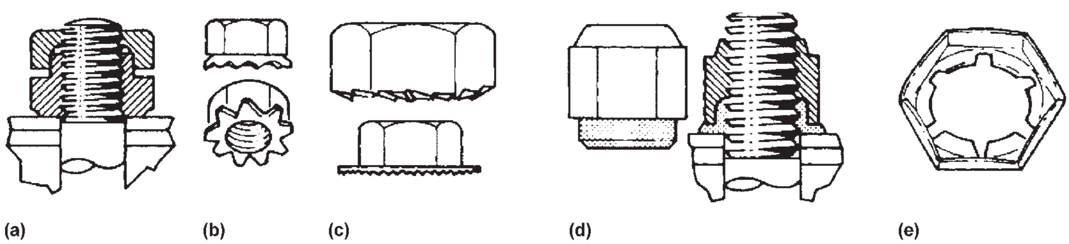


Fig. 8.12 Types of locknuts: (a) the upper half of a two-piece nut presses the collar of the lower half against the bolt; (b) a captive tooth washer provides locking with a spring; (c) ratchet teeth bite into a bearing surface; (d) a nylon insert flows around a bolt to lock and seal; and (e) arched prongs of a single thread lock the unit grip screw. Source: Ref 8.6, p 9.8

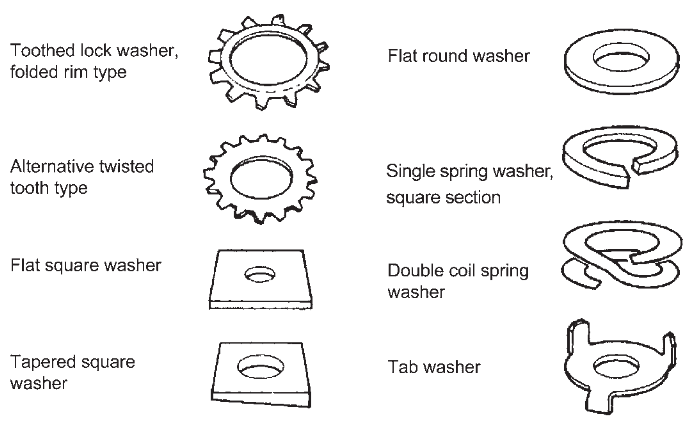


Fig. 8.13 Different types of washers. Source: Ref 8.6, p 9.8

just the bolt head area. For soft materials like wood, this is critical because the bolt head or nut might start to sink into the member surface before an adequate preload is reached. Separation can occur, in addition to the damage of the member surface.

- *Vibration:* Washers help prevent nuts and bolts from coming loose during operation of the joint, especially when vibration is present.
- *Tightening:* Washers make it easier to tighten a bolt and nut joint by keeping them from turning when the other part is turned. This is especially important when it is difficult to get at one side of the joint.
- *Strength:* Although really only an issue when high-strength joints are being used, washers help prevent damage to the nut and bolt from any burrs that might exist from drilling holes. Burrs on the surface can cause failure when high stresses are imposed on the joint.

Self-tapping Screws. These screws fall into two main categories: (a) true self-tapping screws that, like a tap, cut their own threads in a pilot hole; and (b) thread-forming screws that form their own threads by a rolling or swaging action. They are useful in applications where the workpiece material is soft enough to be cut or formed. Similar screws for wood are both self-drilling and self-tapping so that even a pilot hole is not necessary. Self-tapping screws are widely used in the assembly of sheet-metal components in which the thread-cutting action results in a good fit and is resistant to vibration and shock loads. Thread-forming screws are more applicable to thicker materials and blind holes. Self-drilling versions are designed with a true drill point to produce the necessary pilot hole for the threads.

Self-sealing Fasteners. Bolts, screws, washers, and nuts can be made into self-sealing elements by the addition of a sealing element in applications where it is necessary to seal the fastener hole against the leakage of liquids or gases. Sealing mechanisms include rubber O-rings, nylon sleeves, and other elastomeric compounds applied directly to the fastener or to a nut or washer. The choice of the fastener and the sealing material depends on the specific application.

8.4 Pin and Collar Fasteners

Pin and collar fasteners are used for permanent installations, where there is no requirement to remove the fastener. The pin, similar to a bolt, is used with a self-locking or swaged-on collar that cannot be removed with typical tools without destroying the collar or pin. Lock bolts are a common pin and collar fastener that can be installed by either pulling or swaging the collar from the backside. A typical pull-type lock bolt installation sequence is shown in Fig. 8.14. Lock bolts have a series of annular grooves that the collar is swaged into. Once swaged in place, they cannot back off (loosen) and have superior vibration resistance. Lock bolts are available with flush or protruding heads, as shear or tension pull types, and as shear

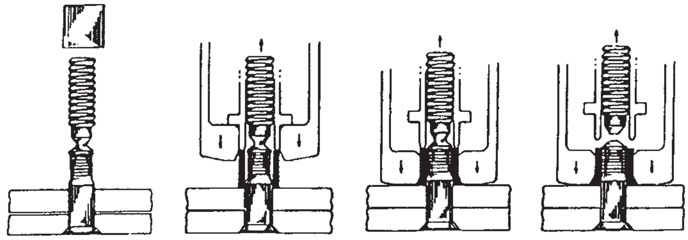


Fig. 8.14 Installation of pull-type lock bolt. Source: Ref 8.1

stump types. Lock bolts are normally lighter and cost less to install than bolt-nut combinations of the same diameter. Two precautions need to be followed when installing lock bolts in thin structure:

- Pull-type lock bolts exert quite a bit of force on the sheet, because of the pulling action necessary to swage the collar onto the pin. If the sheet is thin, fastener pull-through is a real possibility.
- If backside lock bolts (called stump lock bolts) are installed in thin sheets, they should be installed by a piece of automated equipment, where the swaging operation can be carefully controlled.

8.5 Rivets

Riveting is a common and long-used method for permanently fastening parts together. Solid, tubular, and split rivets are among the most commonly used fasteners for assembled products. Rivets are used because they have a favorable relative cost and weight, because they are available in a wide variety of materials, head styles, and sizes, or because they have excellent hole-filling ability. To achieve these benefits, however, a product must be designed for riveting from the beginning, with consideration given to production as well as product design. The five basic types of rivets used are shown in Fig. 8.15. Rivets should be restricted to joints that are primarily loaded in shear with some secondary tension loading allowed, but they should not be used where the primary loads are tension.

The rivet, a fastener with a head on one end and a smooth shank, is inserted through aligned holes in the parts to be joined. The shank end is upset (a head is formed) from force against a die to lock it in place and clamp the parts together. During rivet installation, several physical changes take place: (1) the rivet diameter expands to fill the hole, (2) the hardness of the rivet increases due to work hardening, and (3) the manu-

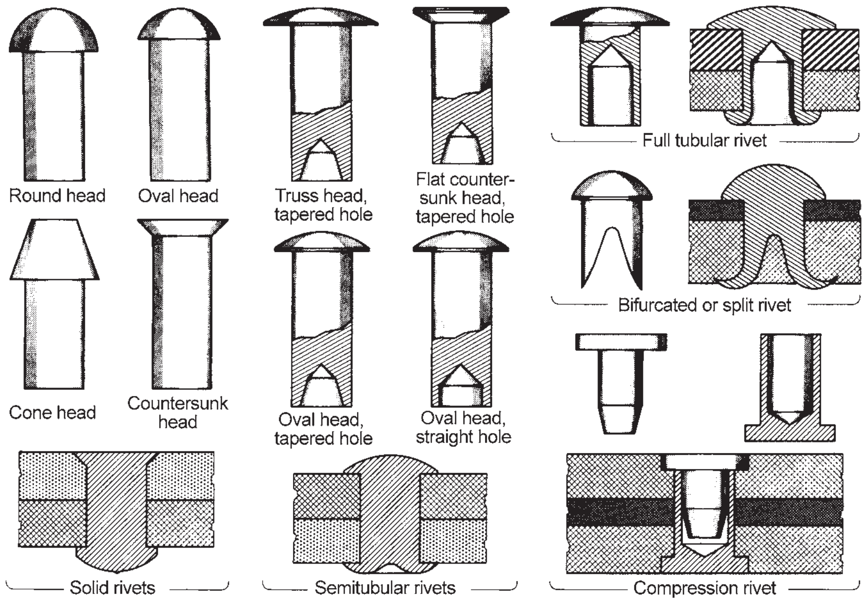


Fig. 8.15 Five basic types of rivets. Source: Ref 8.3

factured head is formed through plastic deformation. One advantage of rivets is that they expand during installation to give a tight fit in the hole.

Upsetting is performed with press force, repeated strokes of a shaped hammer, or orbital motion of the upsetting tool. Tubular and semitubular rivets, split (bifurcated) rivets, and eyelets are typically hopper fed, inserted, and clinched in inexpensive equipment. Traditionally, such equipment has been manually operated with the clinching powered by foot force, air pressure, or electricity. For high-production situations, the operations can be made fully automatic.

Hand-held pneumatic rivet guns are driven by compressed air and are classified as light, medium, and heavy hitting. Light-hitting guns are used to install 2.3 to 3.2 mm (0.09 to 0.125 in.) diameter rivets, while medium-hitting guns are used for 3.8 to 4.8 mm (0.15 to 0.19 in.) diameter rivets. The heavy-hitting guns are used for larger diameters. There are two types of gun sets, one for the universal head rivets and one for countersunk rivets. During manual riveting, a bucking, or backing, bar is used to form the manufactured head during the riveting process. Bucking bars come in different shapes, sizes, and weights. The weight of the bucking bar should be proportional to the size of the rivet being installed.

Self-piercing rivets are those that punch a hole and are inserted in it, all in one operation. These rivets are used with nonmetals and metals to a hardness up to Rb 50. The maximum metal thickness for self-piercing is about 4 mm (0.15 in.). Special machines punch the holes, insert the rivet, and upset the shank end, all in one operation. Tubular and semitubular rivets are clinched in place by flaring the tubular shank end.

Blind rivets are useful when it is not possible to have access to the back side of the riveted assembly. Although holding power is reduced compared to that of conventional rivets, blind rivets can be inserted and clinched easily with hand tools that pull a shaped center plug that expands the tubular shank. Explosive rivets are blind rivets that carry an explosive charge in the shank end. When heat is applied to the rivet, the explosive charge in the shank end is activated, expanding the tubular walls and clinching the rivet. There is no need for heavy axial force.

8.6 Blind Fasteners

Blind fasteners are mechanical fasteners that can be installed in a joint that is accessible from one side only. When a blind fastener is set, a self-contained mechanical, chemical, or other device forms an upset on the inaccessible, or blind, end of the fastener and also expands the fastener shank, thereby securing the parts being joined. Blind fasteners are classified according to the methods by which they are set: pull-mandrel, threaded, drive-pin, or chemically expanded (Fig. 8.16).

A blind-fastened joint is usually in compression or shear, both of which the fasteners can support somewhat better than tensile loading. The amount of loading that blind fasteners subjected to vibration can sustain is influenced by minimum hole clearance and such installation techniques as applying compression to the assembly with clamps before the fasteners are set. Some blind fasteners can be used in material as thin as 0.5 mm (0.02 in.) if the heads are properly formed and if shank expansion is carefully controlled during setting. However, in joining sheets that are dissimilar in thickness, the best practice is to form the blind head against the thicker sheet. Also, if one of the components being joined is a compressible material, rivets with extralarge-diameter heads should be used.

Two types of blind fasteners are the threaded-core bolt type and the pull type (Fig. 8.17). The threaded-core bolt relies on an internal screw mechanism to deform the head and pull it up tight against the structure, whereas the pull-type blind fastener uses a pure pulling action to form the backside head. Higher clamp-up forces and larger footprints are obtainable with the threaded-core bolt, leading to longer fatigue life. However, the pull-types install quicker, are lighter, and are less expensive.

8.7 Machine Pins

The four important types of machine pins are dowel pins, taper pins, clevis pins, and cotter pins. Machine pins are used either to retain parts in a fixed position or to preserve alignment. Under normal conditions, a properly fitted machine pin is subjected to shear loading only, and this occurs only at the interface of the surfaces of the two parts being fastened.

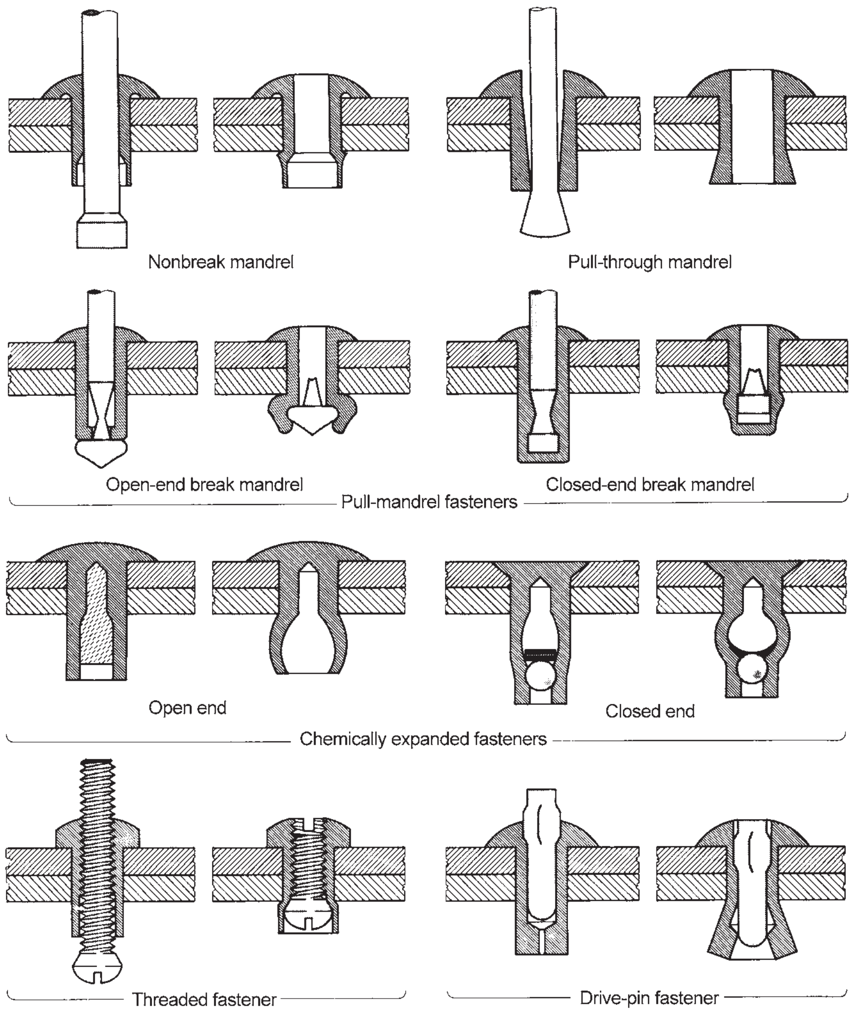


Fig. 8.16 Types of blind fasteners. Source: Ref 8.3

Taper pins are commonly used to fasten parts that are taken apart frequently, where the constant driving out of the pin would weaken the holes if a straight pin were used.

8.8 Presses and Shrink Fits

Presses and shrink fits can be a low-cost method for permanently fastening parts together. The method involves the use of heavy force to drive one part, usually a pin, shaft, or stud, into an undersized hole in another part. In such a fit, the diameter of the male part slightly exceeds the diameter of the female part. The disadvantages of press and shrink fits are that the dimensions of the mating parts must be closely controlled. Pins to be

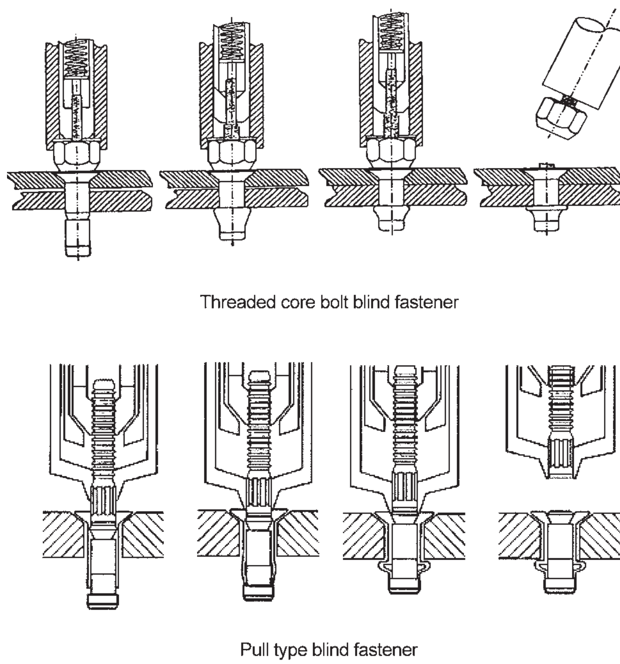


Fig. 8.17 Installation of blind fasteners. Source: Ref 8.1

inserted are often centerless ground to provide an accurate diameter, and the holes to receive them are normally reamed or bored to ensure an accurate internal diameter. Often, the end of the part to be inserted is tapered slightly or the hole is beveled slightly to permit easier initial insertion. In a typical situation, the part to be inserted is manually positioned in the hole and then driven into position with a hand, foot, or powered press. In a shrink fit, the receiving part is heated sufficiently to expand it to the point where the two parts will go together. When it cools, the outer part shrinks around the inserted part, holding it securely.

8.9 Spring Clip Fasteners

Special-purpose fasteners, many of which are proprietary, are frequently used in nonstructural applications to provide some unique feature, such as quick release, snap action, or cam action.

Spring clips (Fig. 8.18) are a type of special-purpose fastener that perform multiple functions, are generally self-retaining, and, for attachment, require only a flange, panel edge, or mounting hole. The spring-tension principle of fastening eliminates loosening by vibration, allows for design flexibility, compensates for tolerance buildup and misalignment, and minimizes assembly damage. The basic material for spring clip fasteners is steel with a carbon content of 0.50 to 0.80%. Fasteners are generally formed in the annealed stage and then hardened and tempered to a hardness of 45 to

Fig. 8.18 Selection of spring clip steel fasteners. Courtesy ACS Manufacturing Inc.

50 Rc. Zinc or cadmium electroplating is specified for certain applications. Other applications may use a zinc mechanical plating to eliminate hydrogen embrittlement that can occur due to electroplating operations.

8.10 Hole Generation and Fastener Installation

Nominal edge distance should be 2*D* from the fastener hole centerline, where *D* is the fastener shank diameter. Nominal distance between fasteners should be *4D*, but this distance can be increased if the dominant load is tension, such as on a pressure vessel port. The *2D* edge distance can be decreased on boss or lug design if the hole is checked for shear tear-out. In thin riveted sheets, such as aircraft panels, inter-rivet sheet buckling can occur if the rivet spacing is too large.

8.10.1 Manual Drilling

Manual or free-hand drilling using hand-held drill motors is one of the most prevalent methods of making a hole, but it also has the least chance of making a close-tolerance hole +0.008/–0.000 mm (+0.003/–0.000 in.). The only real control is the drill speed (rpm). It is up to the operator to make sure the drill is (a) located in the proper location, (b) perpendicular to the surface, and (c) fed with enough pressure to generate the hole but not too much pressure to damage the hole.

Although free-hand drilling is obviously not the best method, it is frequently used because it requires no investment in tooling (i.e., drill templates), and in many applications where access is limited, it may be the only viable method. For tight-access areas, right-angle drill motors are available. If free-hand drilling is used, it is recommended that the operators use a drill bushing, or tripod support, to ensure normality.

During drilling, it is important to use a sharp drill bit because it: (a) will not wander as easily as a dull one, (b) drills faster, and (c) requires lower forces, minimizing the possibility of injury or part damage. Manual hole drilling during assembly is often done by drilling undersize holes (pilot holes), installing temporary fasteners to the hold the parts together, and then bringing the holes up to full size after all of the pilot holes are drilled. Pilot holes are usually drilled with small-diameter drill bits (e.g., 2.3 to 3.2 mm, or 0.90 to 0.125 in.). When drilling multimaterial stack-ups, it is important to make sure they are securely clamped together.

After all the holes have been drilled, the assembly should be taken apart and the holes deburred on both surfaces. Holes should only be deburred with a deburring tool or a drill bit of a larger size. Holes should be deburred by hand due to the danger of hole enlargement if a power drill is used. During all hole-drilling operations, it is important that proper edge distances are maintained, to ensure that the skins do not fail due to inadequate shear strength.

8.10.2 Automated Drilling

For high-volume hole generation, automated drilling equipment can be designed and built for specific applications. Being large and sophisticated machine tools, these units are expensive, so the number of holes drilled and the number of units produced need to be large enough to justify the equipment investment. These machines are extremely rigid and allow for accurate hole location and normality. They are numerically controlled (NC), so there is no need for drill templates. Some have a vision system that can scan the substructure and software that will then adjust the hole location to match where the substructure is actually located, versus design nominal. All drilling parameters are automatically controlled with the capability to change speeds and feeds, when drilling through different materials. All drilling data are automatically recorded and stored for quality control purposes. The drill holders can contain bar codes that must match the drilling program to make sure the correct drills are used for the correct holes. These machines can also install temporary fasteners to clamp the skins to the substructure during drilling, and they frequently use integral drill-countersink cutters that drill the hole and then continue to countersink it during the same operation.

8.10.3 Automated Riveting Equipment

Automated riveting equipment will drill the hole, inspect the hole, select the correct grip length of rivet, install sealant on the rivet (if required), and then install the rivet by squeezing. This equipment is available in a wide variety of sizes, ranging from small units to very large computer numerically controlled (CNC) units. Being an automated process, the quality of drilling and fastener installation is better and more consistent than with manual methods. There are also units that will install pin and collar fasteners, such as lock bolts, where the collar is automatically swaged onto the collar portion of the pin.

8.10.4 Drill Bit Geometries

Many variations of twist drills are used in drilling metallic structure (Fig. 8.19). Because specific drill bit geometries can influence both hole quality and the quantity of holes drilled, many geometries are proprietary to the various manufacturers. Examples of typical variations in the standard twist drill include step drills that drill an undersize hole and then a final hole size in one pass, and drill reamers in which a hole is drilled and then reamed in the same pass. When drilling unhardened steel or aluminum, standard high-speed steels, such as M2 or M7, give satisfactory drill life. For harder materials, such as titanium, the cobalt grades of high-speed steel, such as M33 or M42, yield longer lives. Carbide drills, such as grade C-2, give even longer life in hard materials but are more prone to chipping on the cutting edges.

8.10.5 Fastener Installation

Threaded fasteners are probably the most common type of fasteners. In low-quantity production, they can be started manually and tightened with a hand screwdriver or wrench. In high-production situations, they can be started and driven with special equipment that feeds the fastener from a magazine or a vibratory hopper, inserts it in the appropriate opening, and rotates and tightens it with automatic torque control. When production quantities are intermediate, insertion may be manual followed by the use of a powered driver, positioned either manually or automatically. Powered drivers can be electrical or pneumatic. Impact, impulse, or shutoff wrenches can be adjusted to apply the proper torque to the threaded fastener. Robotic assembly is possible with robots that obtain or contain the fastener, position it, and drive it. These more sophisticated methods require sufficient production quantities so that the cost of obtaining or developing and setting up the equipment can be amortized.

Before installing threaded fasteners in structure, it is important to measure the grip length of the fastener to be installed. Commercial gages are available that can be placed through the hole to measure the correct grip length. In determining fastener grip length for threaded fasteners, it is important that the fastener is long enough that the threads are never loaded in bearing or shear; that is, no threads should be allowed in the hole. In addi-

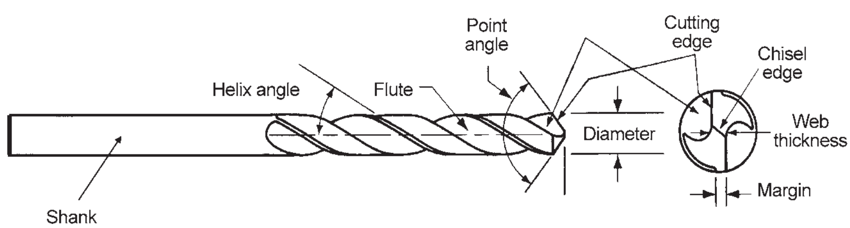


Fig. 8.19 Twist drill geometry. Source: Ref 8.1

tion, no more than three and no less than one thread should be showing when the nut is installed and tightened to the proper torque.

8.10.6 Fatigue Improvement and Interference Fit Fasteners

Since fatigue cracks often initiate at fastener holes in metallic structure, methods such as cold-working fastener holes and interference fit fasteners have been developed to improve fatigue life. Both cold-working and interference fit fasteners set up residual compressive stress fields in the metal immediately adjacent to the hole (Fig. 8.20). The applied tension stress during fatigue loading must then overcome the residual compressive stress field, before the hole becomes loaded in tension. The fatigue improvement due to cold working in 2024-T851aluminum is shown in Fig. 8.21. Somewhat surprisingly, the fatigue strength of the material with a tight fastener in a cold-worked hole is actually somewhat better than the base material.

Cold working of holes is usually conducted using either the split-sleeve or split-mandrel method. Both methods involve pulling a mandrel through the hole that expands the hole diameter, creating plastic deformation of material around the hole and a resulting residual compressive stress field. The residual stress field, depending upon the material and the amount of

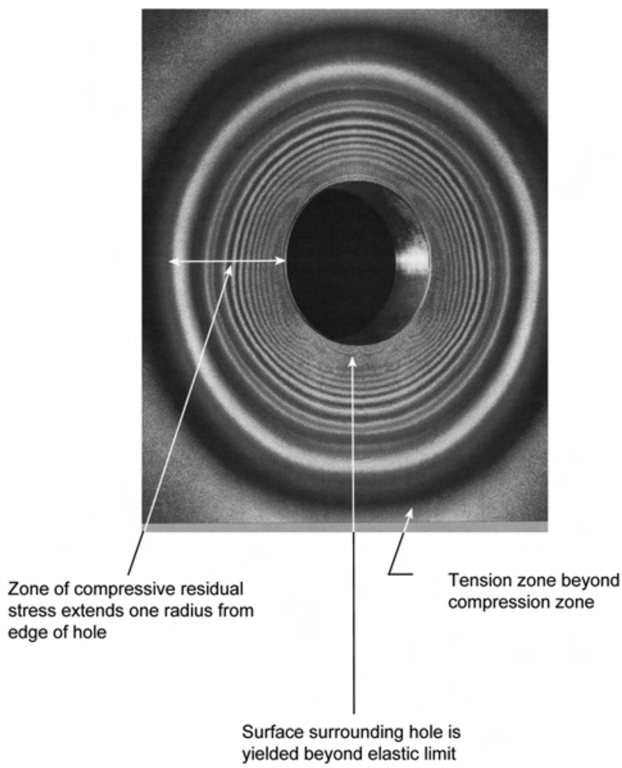


Fig. 8.20 Residual stress state around cold-worked hole. Source: Ref 8.7, Courtesy Fatigue Technology, Inc.

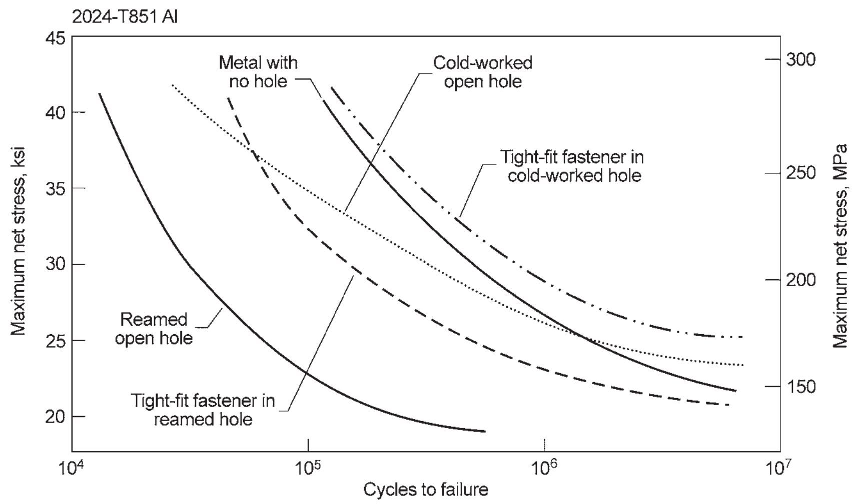


Fig. 8.21 Fatigue life improvement with cold working. Source: Ref 8.7

expansion, will extend approximately one radius from the edge of the hole. In the split-sleeve process, a stainless steel split sleeve is placed over a tapered mandrel and inserted into the hole. The hole is cold worked when the largest part of the mandrel is drawn back through the sleeve. After cold working, the sleeve is removed and discarded. In the split-mandrel process, a collapsible mandrel is placed in the hole, and as the mandrel is withdrawn, it expands to cold work the hole.

Interference fit fasteners are also frequently used in metallic structure to improve the fatigue life. When the interference fit fastener is installed in metal, it also plastically deforms a small zone around the hole, setting up a compressive stress field, which again is beneficial when fatigue loading is primarily in tension. The amount of interference can vary, depending on structural requirements, but it is usually in the range of 0.076 to 0.100 mm (0.003 to 0.004 in.). In some highly loaded holes, both cold working and interference fit fasteners are used. While both cold working and the use of interference fit fasteners are proven methods of improving fatigue resistance, both increase assembly costs and should be specified only when they are really needed.

8.11 Miscellaneous Mechanical Fastening Methods

Stitching and Stapling. Stitching and stapling (Fig. 8.22) are useful for fastening sheet materials, primarily nonmetals, but they can be used with sheets of softer metals. The fasteners are made from either coiled wire or wire preformed into a U-shape and fed from a magazine. With both types, the wire ends are mechanically driven through the sheets to be joined without any holes made beforehand. A forming die, held below the sheets, clinches the wire. The operation, on a semiautomatic basis, has been in existence for many years, with operators using stitching or stapling machines. These machines are operated by foot pressure, pneumatic, or electrical force. Fully automatic equipment is used if production quantities are sufficient. Stitching and stapling are rapid and low in materials costs. The process can be used with fiber, paper, wood, plastics, leather, fabric, and some metal parts. Stitching is commonly used to fasten a sheet to a wood backing. It can also be used to fasten wires, tubes, or rods up to about 6.3 mm (0.250 in.) in diameter to a sheet with a suitable die to clinch the wire around the item fastened. Cold-rolled steel sheets to 14 gage (2 mm, or 0.08 in.) have been stitched together.

Snap Fits. Snap fits occur when the parts to be assembled are designed so that the act of assembly engages elements on the parts that cause them to be held together. These elements normally incorporate some flexibility of one or both of the parts, creating a snap or click when the parts engage. The snap fit approach (Fig. 8.23) is most common in plastics, which have some flexibility and where it is relatively easy to mold catches or hook-like elements in the parts. Normally, molding the part involves the inclusion in the mold of some kind of side core, an element of the mold that moves at right angles to the direction of the mold opening and closing. When this core is advanced before the mold fills, it creates an undercut in the molded part that provides the holding action. When the core retracts, the hooked or socketed part is free to be ejected from the mold when it opens. Snap fits can also be incorporated in many sheet metal parts. The forming die

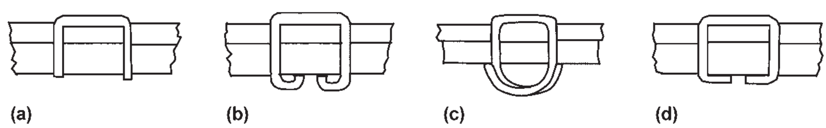


Fig. 8.22 Common types of wire stitches: (a) unclinched, (b) standard loop, (c) bypass loop, and (d) flat clinch. Source: Ref 8.5

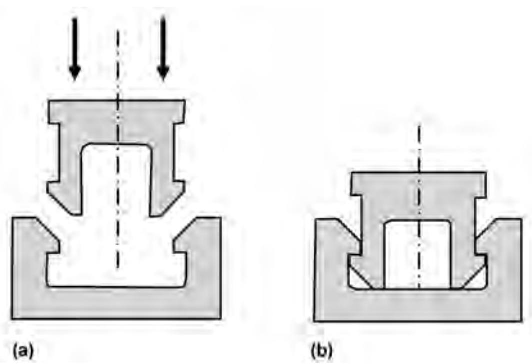


Fig. 8.23 Example of snap fit connection: (a) before assembly, and (b) with parts snapped together

for such parts can have a cammed punch that pierces and bends the sheet metal to form a catch or hook. The advantage of snap fits is that they eliminate the need for screw fasteners, welds, or other means of attachment that involve additional parts and additional operations. Snap fits not only save labor and eliminate some factory operations but also reduce the need to purchase and inventory fasteners that otherwise would be needed. Usually, a simple direct engagement of the parts also engages the snap fit elements.

Integral Fasteners. Integral fasteners involve deformation of component parts so that they interlock and create a mechanically fastened joint (Fig. 8.24). This assembly method is most common for sheet metal parts. Lanced parts (Fig. 8.24a) are used to attach wires or shafts to sheet metal parts. Embossed protrusions (Fig. 8.24b) are sheet metal locations where bosses are formed in one part and then flattened over the mating assembly part. In seaming (Fig. 8.24c), the edges of two separate sheet metal parts or the opposite edges of the same part are bent over to form the fastening

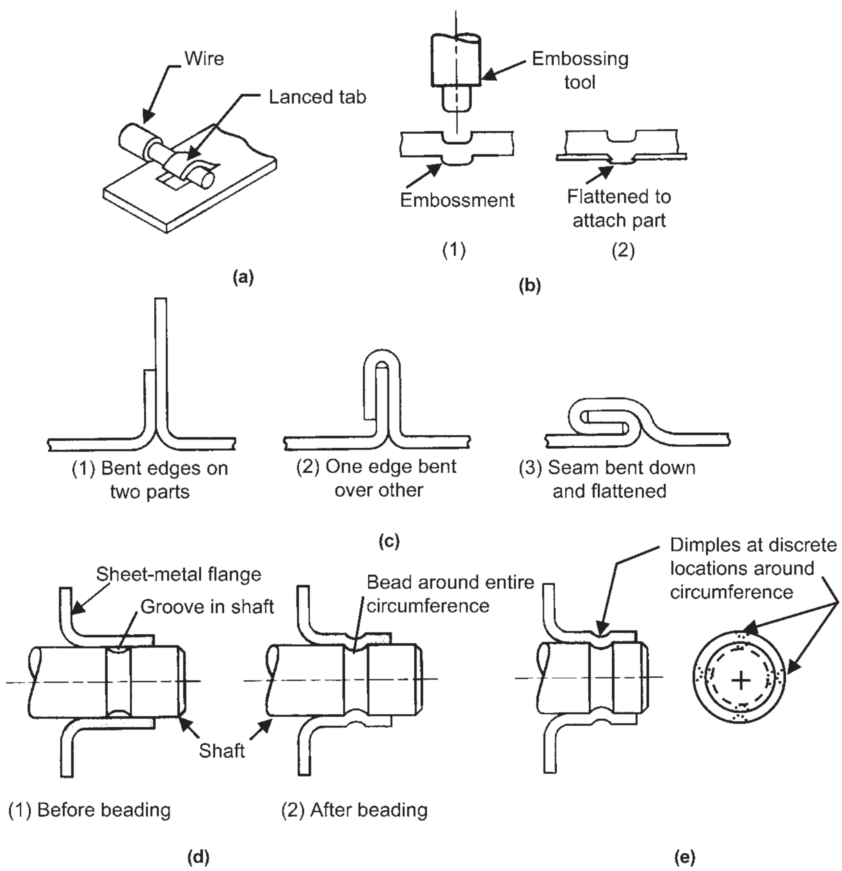


Fig. 8.24 Integral fasteners: (a) lanced tabs to attach wires or shafts to sheet metal, (b) embossed protrusions similar to rivets, (c) single-lock seaming, (d) beading, and (e) dimpling. Source: Ref 8.5

seam. In beading (Fig. 8.24d), a tube-shaped part is attached to a smaller shaft (or other round part) by deforming the outer diameter inward to cause an interference around the entire circumference. Dimpling (Fig. 8.24e) is similar to beading except that the interference is localized to several points around the circumference.

ACKNOWLEDGMENTS

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CHAPTER 9

Adhesive Bonding

ADHESIVE BONDING is a widely used industrial joining process in which a polymeric material (the adhesive) is used to join two separate pieces (the adherends or substrates). This joining technique involves glues, epoxies, or various plastic agents that bond by evaporation of a solvent or by cure with heat, pressure, and time. Historically, adhesives have produced relatively weak bonds. However, the revolution in polymer science that occurred during the 20th century has allowed adhesives with strengths approaching that of the bonded materials themselves. As a result, adhesive bonding has replaced other joining methods in many applications.

Many adhesives make superior stress-bearing components. Whether bonding metal to metal, plastic, glass, rubber, ceramic, or another substrate material, adhesives distribute stress load evenly over a broad area, reducing stress on the joint. Since they are applied inside the joint, adhesives are invisible within the assembly. Many can resist flex and vibration stresses. They also form a seal as well as a bond, which can protect the joint from corrosion. Adhesives easily join irregularly shaped surfaces with a negligible weight increase, create virtually no change in part dimensions or geometry, and quickly and easily bond dissimilar substrates and heat-sensitive materials.

Bonded joints may be preferred if thin sections are to be joined where the bearing stresses in bolted joints would be unacceptably high, or when the weight penalty for mechanical fasteners is too high. In general, thin structures with well-defined load paths are good candidates for adhesive bonding, whereas thicker structures with complex-load paths are better candidates for mechanical fastening.

9.1 Advantages of Adhesive Bonding

The advantages of adhesive bonding include:

- Bonding provides a more uniform stress distribution than mechanical fasteners by eliminating the individual stress concentration peaks caused by mechanical fasteners. The stress distribution across the joint is much more uniform for the adhesive bonded joint than for the mechanical joint (Fig. 9.1), leading to better fatigue life. Bonded joints also provide superior vibration and damping capability.
- Because of the elimination of mechanical fasteners, bonded joints are usually lighter than mechanically fastened joints and are less expensive in some applications.
- Bonded joints enable the design of smooth external surfaces and integrally sealed joints with minimum sensitivity to fatigue crack propagation. Dissimilar materials can be assembled with adhesive bonding, and the joints are electrically insulating, preventing galvanic corrosion of metal adherends.
- Bonded joints provide a superior stiffening effect compared with riveted or spot-welded constructions. While rivets or spot welds provide local point stiffening, bonded joints provide stiffening over the entire bonded area. The significance of this effect is shown in Fig. 9.1, where

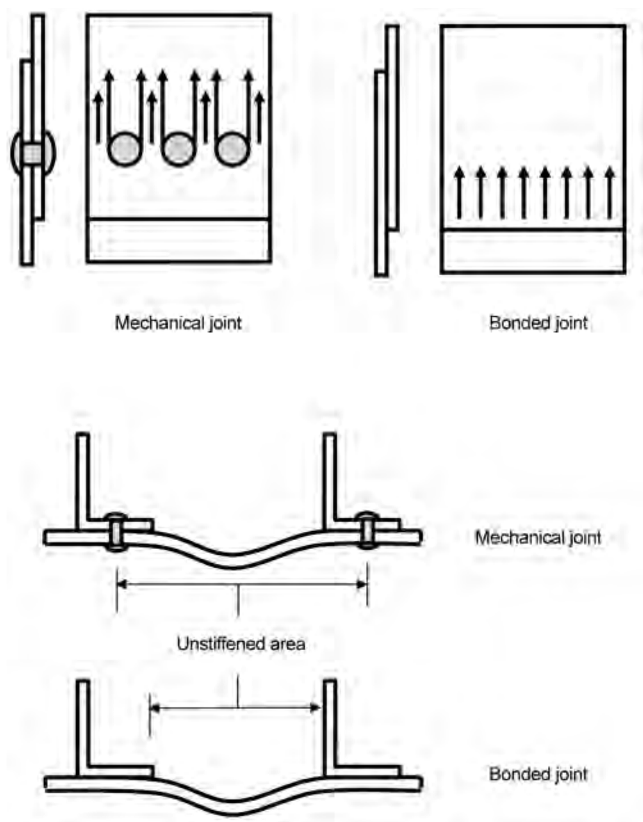


Fig. 9.1 Load distribution comparison for mechanically fastened and bonded joints. Source: Ref 9.1

bonded joints may increase the buckling strength of the structure by as much as 30 to 100%.

9.2 Disadvantages of Adhesive Bonding

Adhesive bonding also has some disadvantages, including:

- Bonded joints should be considered permanent joints. Disassembly is not easy and often results in damage to the adherends and surrounding structure.
- Adhesive bonding is much more sensitive to surface preparation is than mechanical fastening. *Proper surface preparation is absolutely essential to producing a strong, durable bond.* For field repair applications, it can be extremely difficult to execute proper surface prepa ration. For original manufacturing, adhesive bonding requires clean rooms with temperature and humidity control.
- Adhesively bonded joints can be nondestructively tested for the presence of voids and unbonds; however, at this time there is no reliable nondestructive test method for determining the strength of a bonded joint. Therefore, process control test specimens must be fabricated and destructively tested using the same surface preparation, adhesive, and bond cycle as the actual structure.
- Adhesive materials are perishable. They must be stored according to the manufacturer's recommended procedures (often refrigerated). Once mixed or removed from the freezer, they must be assembled and cured within a specified time.
- Adhesives are susceptible to environmental degradation. Most will absorb moisture and exhibit reduced strength and durability at elevated temperature. Some are degraded by chemicals such as paint strippers or other solvents.

9.3 Theory of Adhesion

Despite numerous theories on the nature of adhesion during adhesive bonding, there is some general agreement about what leads to a good adhesive bond. Surface roughness plays a key role: the rougher the surface, the more surface area available for the liquid adhesive to penetrate and lock onto. However, for this to be effective, the adhesive must wet the surface, a function of adherend cleanliness, adhesive viscosity, and surface tension. The importance of surface cleanliness cannot be overemphasized—it is one of the cornerstones of successful adhesive bonding.

In metals, coupling effects as a result of chemical etchants/anodizers or other treatments can also play a role in adhesion by providing chemical end groups that attach to the metal adherend surface and provide other end groups that are chemically compatible with the adhesive.

Therefore, for the best possible adhesive joint, the following areas must be addressed: the surface must be clean and have maximum surface area through mechanical roughness, the adhesive must flow and thoroughly wet the surface, and the surface chemistry must be such that there are attractive forces on the adherend surface to bond to the adhesive.

Surface preparation of a material before bonding is the keystone upon which the adhesive bond is formed. Extensive field service experience with structural adhesive bonds has repeatedly demonstrated that adhesive durability and longevity depend on the stability and bondability of the adherend surface. The effects of several different surface preparations on aluminum adherends are shown in Fig. 9.2. Phosphoric acid anodizing (PAA) and chromic acid anodizing (CAA) are both considered acceptable surface preparations for aluminum, whereas plain grit blasting and solvent degreasing are not. Note that although the grit blast and solvent degrease give somewhat respectable numbers in the as-bonded condition, they quickly degrade under heat and moisture.

For metals, surface preparation involves both the removal of weak boundary layers or layers that are chemically incompatible with the adhesive, and the formation of stable, adherent layers that are mechanically and chemically compatible. A general conclusion of many adhesive bonding studies conducted within the last 25 years is that bond durability is significantly enhanced when the adherend surface contains a significant degree of microscopic roughness, as measured in nanometers. Chemical pretreatments of metal adherends are necessary to obtain microscopic surface roughness. On the other hand, pretreatments such as grit blasting produce macroscopic roughness, which is defined as features on the order of

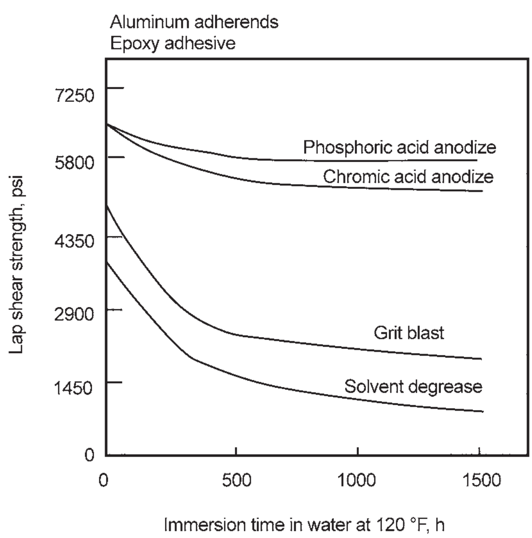


Fig. 9.2 Effect of different aluminum surface treatments on epoxy adhesive bond durability. Source: Ref 9.2

micrometers. The surface treatments producing the greatest durability exhibit microscopic roughness. Durability is increased even further when the adherend surface is chemically compatible with the adhesive.

The approach taken to surface preparation depends on the type of metal used. Although it may be possible to prepare atomically clean aluminum and titanium in the laboratory, it is not practical to do so in an industrial environment. Thus, an oxide is usually formed intentionally. This is accomplished by etching or anodization, most often in an acidic medium and less often in an alkaline medium. The resulting oxides are porous, tenaciously adherent to the metal, and in some instances, chemically tailored for the adhesive. Although reactive metals are prepared in this manner, the approach does not work for steel. Because iron oxide forms rather slowly and is only loosely adherent, the most common method of preparing steel is grit blasting, which results only in macroscopic roughness and reduced bond durability. However, it is possible to deposit a microscopic rough, adherent conversion coating on various steel surfaces.

The formation of a suitable oxide layer on aluminum adherends is critical for long-term durability. There have been many instances of adhesively bonded aluminum structures failing when placed in service because of improper surface preparation. A successful adhesive bond requires a systematic approach (Fig. 9.3) consisting of a suitable oxide on the aluminum surface, a corrosion-resistant primer, and a compatible adhesive layer. The oxide layer must be strong enough to resist stresses, residual or applied, at the interface between the oxide and adhesive. In addition, the oxide layer must resist hydration of diffused moisture to protect the aluminum adherends from corrosion. Surface preparation treatments first remove any grease or oil and then remove the existing oxide layer so that it can be replaced with an optimized oxide.

Surface preparation for thermoset polymers is relatively simple. All that is required is a thorough hand sanding to remove the oxidized surface layer. Thermoplastic surface preparation is more complex and usually does not result in joint strengths as high as those obtained with thermosets. This is believed to be due primarily to the differences in surface chemistry between thermosets and thermoplastics. Thermoplastics contain rather inert, nonpolar surfaces that impede the ability of the adhesive

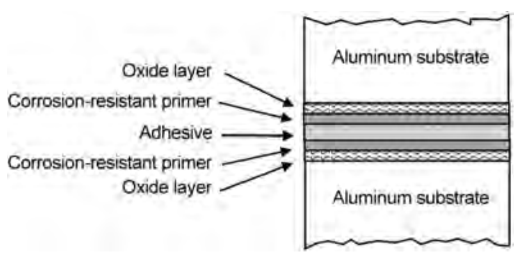


Fig. 9.3 Aluminum adhesive bonded system. Source: Ref 9.2

to wet the surface. Thermoplastic surfaces usually require physical or chemical modification to achieve acceptable bonding.

Some general guidelines for surface treatment for metallic and polymer materials are given in Table 9.1. For a more detailed description of surface preparation techniques for plastics and polymer matrix composites, see Chapter 10.

9.4 Joint Design

In a structural adhesive joint, the load in one component is transferred through the adhesive layer to another component. The load transfer efficiency depends on the joint design, the adhesive characteristics, and the adhesive/substrate interface. To transfer loads effectively through the adhesive, the substrates (or adherends) are overlapped so that the adhesive is loaded in *shear*. Typical joint designs are shown in Fig. 9.4.

As shown in the shear stress distribution for a typical joint (Fig. 9.5), the loads peak at the joint ends while the center portion of the joint carries a much lower portion of the load. Therefore, adhesives designed to carry high loads need to be strong and tough, especially if there is any bending in the joint that would induce peel loads. To improve fracture toughness and fatigue life, brittle epoxy adhesives are frequently modified with rubber or other elastomers that reduce the adhesive modulus. A comparison of a "brittle" high-strength, high-modulus epoxy adhesive with a "ductile" lower-strength, lower-modulus modified epoxy adhesive is shown in Fig. 9.6. While the brittle high-strength adhesive has the highest strength, the

Table 9.1 Characterization of surface treatments for metal and polymer substrates

Pretreatment type	Possible effects of pretreatment
Metallic substrates	
Solvent	Removal of most of organic contamination
Mechanical	Removal of most of organic contamination. Removal of weak or loosely adhering inorganic layers, e.g., mill scale. Change to topography (increase in surface roughness). Change to surface chemistry
Conversion coating	Change to topography (increase in surface roughness). Change to surface chemistry, e.g., the incorporation of a phosphate into the surface layers
Chemical (etching, anodizing)	Removal of organic contamination. Change to topography (increase in surface roughness). Change to surface chemistry. Change to thickness and morphology of metal oxide
Polymer substrates	
Solvent	Removal of contaminants and additives. Roughening (e.g., trichloroethylene vapor/polypropylene). Weakening of surface regions if excessive attack by solvent
Mechanical	Removal of contaminants and additives; oxidative
Oxidative	Removal of contaminants and additives. Introduction of functional groups. Change to topography (e.g., roughening with chromic acid treatment of polyolefins)
Plasma	Removal of contaminants and cross-linking (if inert gas used). Introduction of functional groups if active gases such as oxygen are used. Grafting of monomers to polymer surface after activation, e.g., by argon plasma

Source: Ref. 9.3

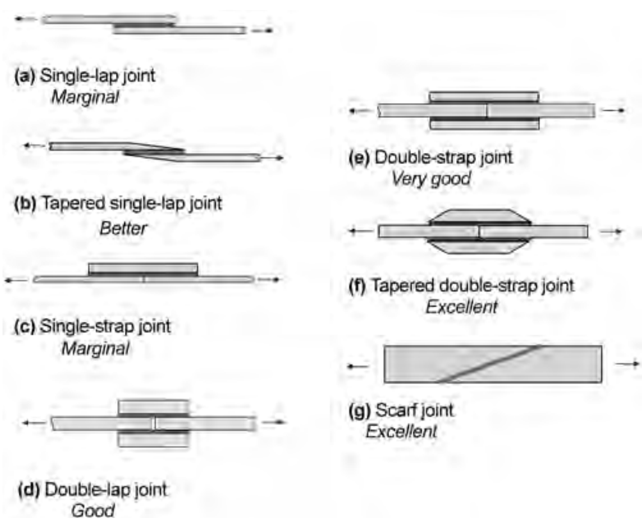


Fig. 9.4 Typical adhesively bonded joint configurations. The adhesive is loaded in shear in all configurations. Source: Ref 9.1

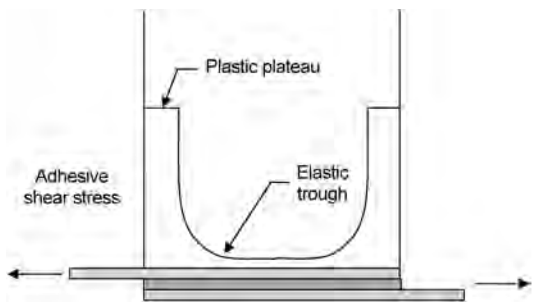


Fig. 9.5 Typical bond line shear stress distribution. Source: Ref 9.4

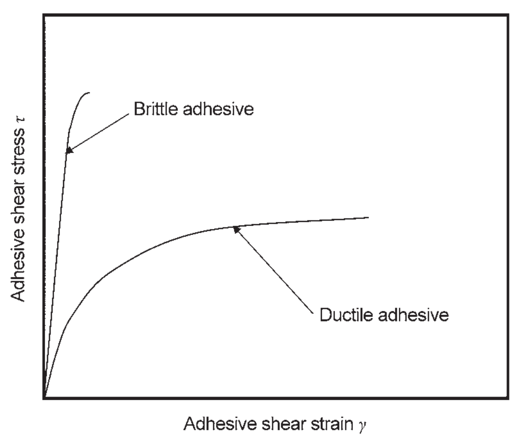


Fig. 9.6 Typical stress-strain behavior for brittle and ductile adhesives. Source: Ref 9.1

tough ductile adhesive, which has a much larger area under the shear stress/strain curve, would be a much more forgiving adhesive, particularly in structural joints that often experience peel and bending loads. The joint design must ensure that the adhesive is loaded in shear as much as possible. Cleavage and peel loading (Fig. 9.7) should be avoided when using adhesives.

Some further considerations for designing adhesively bonded joints are (Ref 9.4):

- The adhesive must be compatible with the adherends and be able to retain its required strength when exposed to in-service stresses and environmental factors.
- The joint should be designed to ensure a failure in one of the adherends rather than a failure within the adhesive bond line.
- Thermal expansion of dissimilar materials must be considered. Because of the large thermal expansion difference between carbon composite and aluminum, adhesively bonded joints between these two materials have been known to fail during cool down from elevated temperature cures as a result of the thermal stresses induced by their differential expansion coefficients.
- Proper joint design should be used, avoiding peel or cleavage loading whenever possible. If peel forces cannot be avoided, a lower-modulus (nonbrittle) adhesive having a high peel strength should be used.
- Tapered ends should be used on lap joints to feather out the edge-of-joint stresses. The fillet at the end of the exposed joint should not be removed.
- Selection tests for structural adhesives should include durability testing for heat, humidity (and/or fluids), and stress, simultaneously.

9.5 Adhesive Testing

Adhesive bond strength is usually measured by the simple single-lap shear test (Fig. 9.8). The lap shear strength is reported as the failure stress in the adhesive, which is calculated by dividing the failing load by the

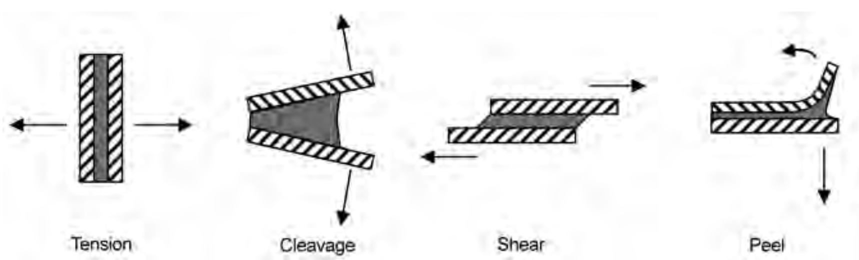


Fig. 9.7 The four basic types of adhesive loading. Tension and shear are acceptable loading methods, provided the bond area is sufficient. Cleavage and peel are to be avoided.

bond area. Since the stress distribution in the adhesive is not uniform over the bond area (it peaks at the edges of the joint, as shown in Fig. 9.5), the reported shear stress is lower than the true ultimate strength of the adhesive. While this test specimen is relatively easy to fabricate and test, it does not give a true measure of the shear strength, because of adherend bending and induced peel loads. In addition, there is no method of measuring the shear strain and thus calculating the adhesive shear modulus required for structural analysis. To measure the shear stress versus shear strain properties of an adhesive, as shown in Fig. 9.6, an instrumented thick-adherend test can be run where the adherends are so thick that the bending forces are negligible. However, the single-lap shear test is an effective screening and process control test for evaluating adhesives and surface preparations and for in-process control. In addition, there are many other tests for characterizing adhesive systems.

When testing or characterizing adhesive materials, several important points should be considered: (1) all test conditions must be carefully controlled, including the surface preparation, the adhesive, and the bonding cycle; (2) tests should be run on the actual joint(s) that will be used in production; and (3) a thorough evaluation of the in-service conditions must be performed, including temperature, moisture, and any solvents or fluids that the adhesive will be exposed to during its service life. The failure modes for all test specimens should be examined. Some acceptable and unacceptable failure modes are shown in (Fig. 9.9). For example, if the specimen exhibits an adhesive failure at the adherend-to-adhesive interface, rather than a cohesive failure within the adhesive, it may be an indication of a surface preparation problem that will result in decreased joint durability.

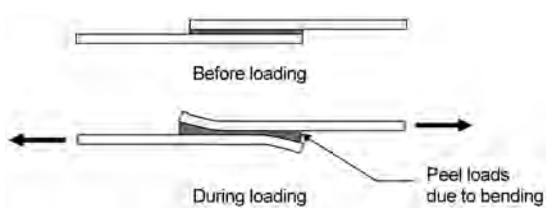


Fig. 9.8 Typical single-lap shear test specimen. Source: Ref 9.1

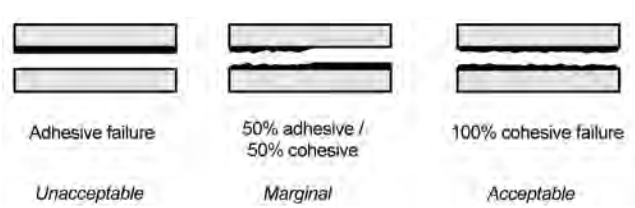


Fig. 9.9 Difference between cohesive and adhesive failure modes. Source: Ref 9.1

9.6 Adhesive Selection

The characteristics of the most important synthetic adhesive systems are (Ref 9.5, p 785):

- *Anaerobic:* Single-component thermosetting acrylic-based adhesive. Cures by free radical mechanism at room temperature. Shear strength to 20 MPa (2900 psi), tensile strength to 40 MPa (5800 psi). Applications: sealant, structural assembly
- *Modified acrylic:* Two-component thermosetting adhesive consisting of acrylic-based resin and initiator/hardeners. Cures at room temperature after mixing. Shear strength to 34 MPa (4900 psi), tensile strength to 25 MPa (3600 psi). Applications: fiberglass in boats, sheet metal in cars and aircraft
- *Cyanoacrylate:* Single-component thermosetting acrylic-based adhesive that cures at room temperature on alkaline surfaces. Tensile strength to 17 MPa (2500 psi). Applications: rubber to plastic, electronic components of circuit boards, plastic and metal cosmetic cases
- *Epoxy:* Includes a variety of widely used adhesives formulated from epoxy resins, curing agents, and filler/modifiers that harden on mixing. Some are cured when heated. Shear strength to 40 MPa (5800 psi), tensile strength to 50 MPa (7200 psi). Applications: aluminum bonding applications and honeycomb panels for aircraft, sheet metal reinforcements for cars, lamination of wood beams, seals in electronics
- *Hot-melt:* Single-component, thermoplastic adhesive hardens from molten state after cooling from elevated temperatures. Formulated from thermoplastic polymers including ethylene vinyl acetate, polyethylene, styrene block copolymer, butyl rubber, polyamide, polyurethane, and polyester. Shear strength to 7 MPa (1000 psi), tensile strength to 9 MPa (1300 psi). Applications: packaging, furniture, footwear, bookbinding, carpeting, and assemblies in appliances and cars
- *Pressure-sensitive tapes and films:* Usually pressure-sensitive adhesives of one component in solid form that possess high tackiness, resulting in bonding when pressure is applied. Formed from various polymers of high molecular weight. Can be single or double sided. Shear strength to 49 MPa (7100 psi), tensile strength to 40 MPa (5800 psi). Applications: solar panels, electronic assemblies, plastics to wood and metals
- *Silicone:* One- or two-component thermosetting liquid adhesive based on silicon polymers. Cures by room temperature vulcanization to rubbery solid. Shear strength to 3 MPa (450 psi), tensile strength to 5 MPa (725 psi). Applications: seals in cars, electronic seals and insulation, gaskets, bonding of plastics
- *Urethane:* One- or two-component thermosetting adhesive based on urethane polymers. Shear strength to 19 MPa (2800 psi), tensile

strength to 50 MPa (7250 psi). Applications: bonding of fiberglass and plastics.

These systems include some that are thermoset and cure by chemical reaction, and some that are thermoplastic and are simply heated above their melting points and then allowed to solidify on cooling. In addition, some are formulated to enable them to carry high loads and are thus classified as structural adhesives, while others are designed to carry little or no load and can often be easily removed. Adhesives can be grouped into the following five groups:

- Structural
- Hot melt
- Pressure sensitive
- Water based
- Ultraviolet (UV) and electron beam (EB) cured

9.6.1 Structural Adhesives

A structural adhesive is a material of proved reliability in engineering structural applications in which the bond can be stressed to a high proportion of its maximum failing load for long periods without failure. Most materials used in structural adhesives are thermosets. However, some are thermoplastics, such as cyanoacrylates and anaerobics. The most widely used structural adhesive groups are epoxies, polyurethanes, modified acrylics, cyanoacrylates, and anaerobics. Their advantages and limitations are listed in Table 9.2, and typical properties are given in Table 9.3. The sections below briefly discuss these and the silicone, phenolic, and high-temperature adhesive chemical families.

Epoxies. Epoxy-based adhesives are by far the most commonly used materials for structural bonding. Epoxy adhesives impart high-strength bonds and long-term durability over a wide range of temperatures and environments. The ease with which formulations can be modified makes it fairly easy for the epoxy adhesive formulator to employ various materials to control specific performance properties, such as density, toughness, flow, mix ratio, pot life/shelf life, shop handling characteristics, cure time/temperature, and service temperature.

Advantages of epoxy adhesives include excellent adhesion, high strength, low or no volatiles during cure, low shrinkage, and good chemical resistance. Disadvantages include cost, brittleness unless modified, moisture absorption that adversely affects properties, and relatively long cure times. A wide range of one- and two-part epoxy systems are available. Some systems cure at room temperature, while others require elevated temperatures.

Epoxy resins used as adhesives are generally supplied as liquids or low-melting-temperature solids. The rate of the reaction can be adjusted by

Table 9.2 Advantages and limitations of the five most widely used chemically reactive structural adhesives

Advantages				
Epoxy	Polyurethane	Modified acrylic	Cyanoacrylate	Anaerobic
High strength Good solvent resistance Good gap-filling capabilities Good elevated-temperature resistance Wide range of formulations Relatively low cost	Varying cure times Tough Excellent flexibility even at low temperatures One or two components, room- or elevated-temperature cure Moderate cost	Good flexibility Good peel and shear strengths No mixing required Will bond dirty (oily) surfaces Room-temperature cure Moderate cost	Rapid room-temperature cure One component High tensile strengths Long pot life Good adhesion to metal Dispenses easily from package	Rapid room-temperature cure Good solvent resistance Good elevated-temperature resistance No mixing Indefinite pot life Nontoxic High strength on some substrates Moderate cost
Limitations				
Epoxy	Polyurethane	Modified acrylic	Cyanoacrylate	Anaerobic
Exothermic reaction Exact proportions needed for optimum properties Two-component formulations require exact measuring and mixing One-component formulations often require refrigerated storage and an elevated-temperature cure Short pot life (more waste)	Both uncured and cured are moisture sensitive Poor elevated-temperature resistance May revert with heat and moisture Short pot life Special mixing and dispensing equipment required	Low hot-temperature strength Slower cure than with anaerobics or cyanoacrylates Toxic Flammable Odor Limited open time Dispensing equipment required	High cost Poor durability on some surfaces Limited solvent resistance Limited elevated-temperature resistance Bonds skin	Not recommended for permeable surfaces Will not cure in air as a wet fillet Limited gap cure

Source: Ref. 9.6

Table 9.3 Typical properties of the five most widely used chemically reactive structural adhesives

Property	Epoxy	Polyurethane	Modified acrylic	Cyanoacrylate	Anaerobic
Substrates bonded	Most	Most smooth, nonporous	Most smooth, nonporous	Most nonporous metals or plastics	Metals, glass, thermosets
Service temperature range, °C (°F)	–55–121 (–67–250)	–157–79 (–250–175)	–73–121 (–100–250)	–55–79 (–67–175)	–55–149 (–67–300)
Impact resistance	Poor	Excellent	Good	Poor	Fair
Tensile shear strength, MPa (ksi)	15.4 (2.20)	15.4 (2.20)	25.9 (3.70)	18.9 (2.70)	17.5 (2.50)
T-peel strength, N/m (lbf/in.)	<525 (3)	14,000 (80)	5250 (30)	<525 (3)	1750 (10)
Heat cure or mixing required	Yes	Yes	No	No	No
Solvent resistance	Excellent	Good	Good	Good	Excellent
Moisture resistance	Excellent	Fair	Good	Poor	Good
Gap limitation, mm (in.)	None	None	0.762 (0.030)	0.254 (0.010)	0.635 (0.025)
Odor	Mild	Mild	Strong	Moderate	Mild
Toxicity	Moderate	Moderate	Moderate	Low	Low
Flammability	Low	Low	High	Low	Low

Source: Ref. 9.6

adding accelerators to the formulation or by increasing the cure temperature. To improve structural properties, particularly at elevated temperatures, it is common to use cure temperatures close to (or preferably above) the maximum use temperature. Epoxy resin systems are usually modified with a wide range of additives that control particular properties, including accelerators, viscosity modifiers and other flow control additives, fillers and pigments, flexibilizers, and toughening agents. Epoxy-based adhesives are available in two basic cure chemistries: room-temperature and elevated-temperature cure.

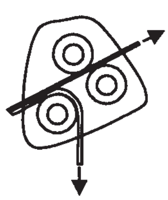
The properties of two toughened and two untoughened epoxy film adhesives are shown in Table 9.4. Toughened epoxy adhesive (1) is cured at 120 ºC (250 °F) and has a recommended maximum usage temperature of 82 ºC (180 °F). It has a combination of a high single-lap shear strength (41.4 MPa or 6000 psi) and peel strength (70 pounds per linear inch, or pli) when tested at room temperature. The toughened epoxy adhesive (2) has a higher usage temperature (150 ºC, or 300 °F) that results in a somewhat lower single-lap shear strength (35 MPa, or 5,080 psi) and peel strength (29 pli). The lower strength and peel resistance are a trade-off to obtain a higher usage temperature. The two untoughened epoxy adhesives have even lower lap shear strengths (29 and 28 MPa, or 4200 and 4100 psi) and, since they are not toughened, dramatically lower peel strengths (3 and 8 pli). Toughening of epoxy adhesives is often accomplished by the addition of liquid rubber compounds (e.g., ≈ 15% carboxyl-terminated butadiene rubber) that precipitates during cure. The rubber toughener increases the strength and peel resistance but also lowers the maximum usage temperature, as illustrated by the lower glass transition temperatures for the two toughened epoxy adhesives shown in Table 9.4.

It is significant that the data shown in Table 9.4 are for short-term elevated temperature exposures. The untoughened adhesive (2) has a single-lap shear strength of 20 MPa (2900 psi) at 216 ºC (420 °F), but this is for an extremely short exposure at elevated temperature, and no moisture conditioning was performed. Since moisture lowers the glass transition temperature of adhesives, it is extremely important to test adhesives under

Table 9.4 Properties of several epoxy film adhesives

Adhesive type	Toughened epoxy 1	Toughened epoxy 2	Untoughened epoxy 1	Untoughened epoxy 2
Cure temperature °C (°F)	120 (250)	177 (350)	177 (350)	177 (350)
Glass transition temperature °C (°F)	95 (203)	147 (296)	174 (345)	178 (352)
Maximum usage temperature °C (°F)	82 (180)	150 (300)	177 (350)	216 (420)
Room temp. single-lap shear MPa (psi)	42 (6000)	35 (5080)	29 (4200)	28 (4100)
Metal-to-metal peel (pli)(a)	70	29	3	8
Single lap shear @ service temper-sture °C (°F)	4240 @ 82 (180)	2900 @ 149 (300)	3100 @ 177 (350)	1850 @ 216 (420)

Increasing temperature usage →



(a) Metal-to-metal peel can be measured by the rolling ball method. Results are reported as pounds per linear inch (pli). Source: Ref. 9.2

the same environmental conditions as the actual structure will experience in service. In fact, the reported dry glass transition temperature of untoughened adhesive (2) of 178 ºC (352 °F) is lower than the recommended maximum usage temperature of 216 ºC (420 °F). Unless the time at temperature is extremely short, it is never sound practice to use an adhesive or matrix resin system at a temperature higher than its glass transition temperature.

Two-part liquid and paste epoxies are most commonly used when a room-temperature cure is desired. They are available as clear liquids, or as filled pastes, with a consistency ranging from low-viscosity liquids to heavy-duty putties. Typical cure times at room temperature are 5 to 7 days; however, in most cases, 70 to 75% of the ultimate cure can be achieved within 24 h and, if needed, the pressure can usually be released at that point. Under normal bond-line thickness conditions (0.13 to 0.25 mm, or 0.005 to 0.010 in.), cure can be accelerated with heat without fear of exotherm. A typical elevated temperature cure would be 1 h at 82 ºC (180 °F).

Structural adhesives for aerospace applications are generally supplied as thin films supported on a release paper and stored under refrigerated conditions (i.e., –18 ºC, or 0 °F). Film adhesives are preferred to liquids and pastes because of their uniformity and reduced void content. In addition, since film adhesives contain latent curing agents that require elevated temperatures to cure, the adhesives are stable at room temperature for as long as 20 to 30 days. Film adhesives are available using high-temperature aromatic amine or catalytic curing agents, with a wide range of flexibilizing and toughening agents. Rubber-toughened epoxy film adhesives are widely used in the aircraft industry. The upper temperature limit of 120 to 177 ºC (250 to 350 °F) is usually dictated by the degree of toughening required and by the overall choice of resins and curing agents. In general, toughening an adhesive results in a lower usable service temperature. A comparison of the single-lap shear strength of a toughened and untoughened epoxy film adhesives at different temperatures is shown in Fig. 9.10. It is usually desirable to use the toughest adhesive that will meet the operating temperature requirements, because high-strain adhesives are much more forgiving than are unmodified systems. While the two may have similar lap shear strengths, the big advantage of the toughened systems is in joints that may experience some peel.

Polyurethanes. Chemically reactive polyurethanes include both one- and two-component systems. One-component systems are usually based on a polyether polyol reacted with a polyisocyanate, yielding an isocyanate-terminated polymer. A one-component system cures when exposed to moisture at room temperature. Two-component systems result from the reaction of low-molecular-weight polyols and isocyanates or from isocyanate-terminated prepolymers with either polyols or polyamines. Two-component systems cure at room and/or elevated temperatures. Heat-

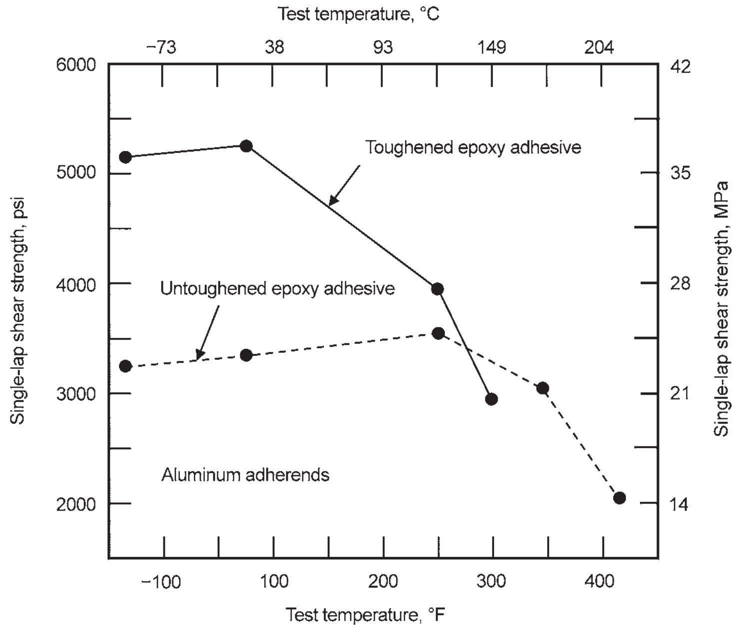


Fig. 9.10 Temperature resistance of two epoxy film adhesives. Source: Ref 9.2

cured polyurethane adhesives are typically cured between 93 and 200 °C (200 and 390 °F). Both types of polyurethane adhesives are available in solvent-free and low-solvent systems.

Polyurethanes bond to most surfaces. They have an outstanding single-lap shear strength of 34.4 MPa (5 ksi) at –73.3 °C (–100 °F). In fact, polyurethanes have better low-temperature strength than any other adhesive. Good flexibility, abrasion resistance, and toughness are other advantages of polyurethanes. Limitations include sensitivity to moisture in both uncured and cured adhesives, toxicity of isocyanate, and poor single-lap shear strength at room temperature (12.4 MPa, or 1.8 ksi).

Modified Acrylics. Modified acrylics, also referred to as second-generation acrylics or reactive acrylics, are composed of a modified acrylic adhesive and a surface activator. Typical modified acrylics are based on crosslinked polymethyl methacrylate grafted to vinyl-terminated nitrile rubber. Carboxy-terminated rubbers have also been used. Both one- and two-component systems are available.

Modified acrylics have good peel, impact, and single-lap shear strengths between –107 and 121 °C (–161 and 250 °F). High bond strengths are obtained with metals and plastics even if surfaces are oily or improperly cleaned. The cured adhesive exhibits little shrinkage. Resistance to high humidity is good, particularly when bonding plastic substrates. The limitations of modified acrylic adhesives include low elevated temperature strength, flammability, and the odor of the uncured acrylic adhesive.

Cyanoacrylates. Cyanoacrylates are single-component liquids that cure when nucleophiles, such as water on the surface of a part, serve as initiation sites for polymerization. No by-products are released during cure. Factors that influence cure include the moisture on the surfaces to be bonded, relative humidity, pH, and bond-line thickness. Problems may be encountered when bonding acidic (low pH) surfaces. Bond lines that are too thick may not cure in the center because water from substrate surfaces may be unable to penetrate completely. Cyanoacrylates are thermoplastic when cured and so are limited in temperature capability and chemical resistance.

Cyanoacrylates will bond to most substrates. Bond durability problems are encountered with silicones, polyolefins, and some fluoroelastomers and with glass, where extensive surface preparation is required. In general, cyanoacrylates require no special curing equipment and have a fast cure, excellent lap-shear strength, and good shelf life. Limitations include high cost, poor peel strength, brittleness, limited elevated temperature properties, and the capability to fill only small gaps.

Anaerobics. Anaerobics are single-component monomeric liquids that cure by polymerization upon the elimination of oxygen. These materials are packaged in contact with air in order to maintain their monomeric form. The adhesives are available in machinery or structural grades. The former provides high cohesive strength in threaded-assembly bonding, and the latter provides high tensile and shear strengths in flat assemblies.

Anaerobic adhesives are applied to three types of surfaces: active, inactive, and inhibiting. Active surfaces include clean metals and thermosets and result in the fastest cure. Inactive surfaces include some metals and plastics, which result in a slow cure. Inhibiting surfaces include bright platings, chromates, oxides, and certain anodizes. Primers or heat must be used to achieve cure on inactive and inhibiting surfaces. Some plastics and rubbers are attacked by anaerobics. Others, such as Teflon, acetal, polyolefins, nylon, and polyvinylidene chloride, can be bonded with anaerobics. Average cure speeds range from fast (5 min to 2 h) to moderate (2 to 6 h) to slow (6 to 24 h) at room temperature in the absence of primers. Heat accelerates the cure.

In general, anaerobic adhesives have a service temperature limit of 149 °C (300 °F) and are moderately priced. Structural anaerobic adhesives have high strength and good moisture, solvent, and temperature resistance. If air is present, it will attack certain thermoplastic and rubber surfaces and also prevent cure.

Silicones. Silicones are available as both one- and two-component systems that cure to thermosetting solids. A one-component room-temperature-vulcanizing silicone cures at room temperature upon exposure to atmospheric moisture. Cures are either acidic or nonacidic in the presence of moisture. Adhesives that have an acidic cure have greater unprimed adhesion and a longer shelf life. However, the corrosion of metals due to the acid is a potential problem. Thin films of approximately 0.6 mm (0.024 in.) cure within 90 min, whereas thicker films of approximately 13 mm (0.512 in.) require 7 days to achieve full cure.

Two-component silicones do not require moisture in order to cure. During the polymerization of these silicones, cure is achieved by catalytic action. Pot life, setting time, and cure time depend on the catalyst concentration. A system with 5% catalyst will typically have a 3 h pot life, a 22 h setting time, and a 7 day cure time at room temperature. Increasing the temperature accelerates the cure. These silicones exhibit little shrinkage upon cure and have good high-temperature resistance.

In general, silicone adhesives have good peel strength over a service temperature range of –60 to 250 °C (–76 to 482 °F). Some have limited service to 371 °C (700 °F). Flexibility and impact resistance are good, as are moisture, hot water, oxidation, and weathering resistance. Typical single-lap shear strengths are low in metal-to-metal bonds, with values ranging between 1.72 and 3.44 MPa (250 and 500 psi). The cost of these adhesives is high. Silicone adhesives are useful in bonding metals, glass, paper, plastics, and rubbers, including silicone, butyl rubber, and fluoroelastomers.

Phenolics. Phenolics, or phenol-formaldehyde structural adhesives, are chemically reactive systems that cure to thermosets. In one-component systems, meltable powders (resoles) are used as binders for particleboard or as alloys (including nitrile-phenolics, vinyl-phenolics, and epoxy-phenolics), which are used in the structural bonding of metals. In two-component systems, the resin and catalyst are mixed and then heated to cure. Both systems cure by a condensation reaction, yielding a gaseous by-product that can result in bond-line voids and porosity.

In general, phenolics are low-cost adhesives having good strength and resistance to biodegradation, hot water, and weathering. Elevated-temperature resistance is also good. Limitations include low impact strength, high shrinkage stresses that lead to brittleness, and the potential for voids and porosity due to the condensation curing reaction. Shelf life is limited, the adhesives are dark in color, and they can be corrosive. Phenolics dominate the wood adhesives market, especially with regard to plywood. The structural adhesive bonding of metals, particularly with phenolic alloys, is another application. Phenolics can be alloyed with nitrile rubber or polyvinyl fluoride to improve toughness and impact resistance.

Epoxy-phenolic adhesives are also available as liquids or films. This adhesive is one of the best for long-term use at 149 to 260 °C (300 to 500 °F). The minimum service temperature is usually –60 °C (–76 °F), although special formulations may be useful at temperatures as low as –260 °C (–436 °F). In general, epoxy-phenolics are relatively expensive. They have fairly good shear and tensile strengths over a wide temperature range.

Impact resistance is poor, whereas resistance to weathering, aging, aromatic fuels, glycols, hydrocarbon solvents, and water is good. Typical applications include the bonding of metals, glass, ceramics, and phenolics.

High-Temperature Adhesives. Structural adhesives having high-temperature resistance are based on synthetic organics having aromatic (benzene) and/or heterocyclic rings in the main structure. High-temperature adhesives include cyanate esters, bismaleimides, and polyimides. Cyanate esters and bismaleimides are both addition-curing polymers that can be used up to 135 to 149 ºC (275 to 300 ºF) after post curing. Although polyimides can be used to temperatures as high as 260 to 288 ºC (500 to 550 ºF), they cure by a condensation reaction that evolves volatiles during cure, which can lead to porous bond lines. Applications of high-temperature adhesives are primarily in the aircraft and aerospace industries for bonding metals and composites that will be exposed to elevated temperatures.

9.6.2 Hot-Melt Adhesives

Hot-melt adhesives are generally 100% solid formulations based on thermoplastic polymers. They are solid at room temperature and become liquids when heated above their melting points. On cooling, they solidify and regain their original physical and mechanical properties. In general, hot-melt adhesives are solid at <79 °C (<175 °F). Ideally, as the temperature is increased beyond this point, the material rapidly melts to a low-viscosity fluid that can be easily applied. Upon cooling, the adhesive sets rapidly. Because these adhesives are thermoplastics, the melting-resolidification process is repeatable with the addition and removal of the required amount of heat. Typical application temperatures of hot-melt adhesives are 149 to 188 °C (300 to 370 °F).

The major hot-melt adhesive chemical families include ethylene/vinyl acetate copolymer, polyethylene, polyvinyl acetates, polybutene, thermoplastic elastomers, polyamides (nylons), and polyesters. The latter two families are sometimes classified as high-performance hot-melt adhesives because of their greater strengths and higher end-use temperatures versus other hot-melt adhesive families. Hot-melt adhesives are available in forms such as pellets, slabs, bars, slugs, and films that allow convenient handling by a variety of application equipment. Special dispensing equipment must be used to apply hot-melt adhesives. Typical application methods include the use of rollers, screw extruders, and squirting pumps or nozzle applicators.

The limitations of hot-melt adhesives are limited toughness at usable viscosities, low heat resistance, and poor creep resistance. All properties are affected by the polymer and diluents used in the formulation. The application conditions, including the amount of adhesive and the pressure applied to the bond line, also affect end-use properties. During the hot-melt adhesive bonding operation, a minimum amount of pressure must be applied until the hot melt becomes solid or sufficient tack develops to hold the substrates in place.

Hot-melt adhesives are used to bond all types of substrates, including metals, glass, plastics, ceramics, rubbers, and wood. Primary areas of application include packaging, bookbinding, assembly bonding (such as air filters and footwear), and industrial bonding, such as carpet tape and backings.

9.6.3 Pressure-Sensitive Adhesives

Pressure-sensitive adhesives are capable of holding together objects when the surfaces are brought into contact under briefly applied pressure at room temperature. The difference between contact adhesives and pressure-sensitive adhesives is that contact adhesives require no pressure to bond. Materials used in pressure-sensitive adhesives must possess viscous properties to provide flow, the capability to dissipate energy during adhesion, partial elastic behavior, the tendency to resist excessive flow, and the ability to store bond rupture energy to provide peel and tack. In other words, pressure-sensitive adhesive materials must be viscoelastic. Pressure-sensitive adhesives are primarily used in tapes and labels, with tapes representing the largest area of application.

The primary families used as the adhesive component in pressure-sensitive adhesives, in order of decreasing volume and increasing price, include natural rubber, styrene-butadiene rubber, reclaimed rubber, butadiene-acrylonitrile rubber, thermoplastic elastomers, polyacrylates, polyvinyl alkyl ethers, and silicones. Pressure-sensitive adhesives are almost always supplied as a coating on a substrate. Substrate materials include paper; cellophane; plastic films, such as polyethylene, polypropylene, polyvinyl chloride, polyester, and polyimide; fabrics; and metallic foils. The coating weight of the adhesive is usually between 20 and 50 g/m^2 (0.066 and 0.164 oz/ft^2). Typical additives may include tackifiers, plasticizers, fillers, stabilizers, and/or pigments.

9.6.4 Water- and Solvent-Based Adhesives

Adhesive materials that can be dissolved or dispersed in water form the basis of water-based adhesives. Many of these same materials are also used in organic solvent-based adhesives. Water-based adhesives in the natural adhesive family include casein, cellulosics, rosin, natural rubber, starch, dextrin, sodium silicate water solutions, and animal glues. Early synthetic water-based adhesives in use before 1960 are based on polyvinyl alcohol, polyvinyl acetate, urea formaldehyde, melamine formaldehyde, phenol formaldehyde, styrene-butadiene rubber, neoprene, reclaimed rubber, nitrile rubber, and polyvinyl methyl ether. Newer synthetic water-based adhesives developed after 1960 are largely based on acrylics. These acrylic-based adhesives are inherently tacky because of the choice of monomers and molecular weights and because of crosslinking. In addition, unlike traditional acrylics, these tackified adhesives have a good balance of peel, shear, and tack properties.

Multicomponent systems based on acrylated silicones, acrylated urethanes, and acrylated silicone urethanes are also available. The addition of silicone results in adhesives with improved thermal stability, tensile strength, and resistance to oil and grease, UV rays, and solvents. Adding urethane increases toughness, thermal stability, and resistance to solvents, abrasions, and UV rays. In particular, the silicone- and urethane-based acrylates have improved adhesion to ceramics, fiberglass, and metals.

In recent years, exposure to organic solvents has been increasingly controlled by federal regulations. Therefore, it is advantageous to use water-based rather than organic-solvent-based adhesives. The use of water as a solvent results in lower cost, nonflammability, and lower toxicity. It also makes it possible to vent drying ovens directly into the atmosphere. In addition, many water-based adhesives can be substituted for organic-solvent-based adhesives with no modification to application equipment. Water-based adhesives have fairly good organic-solvent resistance. However, moisture resistance is usually poor, and adhesives are subject to freezing, which can affect properties.

Although there are many advantages to using water-based adhesives, there is still a large and important market for solvent-based adhesives. Water-based adhesives are usually unsuitable for hydrophobic surfaces, such as plastics, because of poor wettability. In addition, water shrinks some substrates, such as paper, textiles, and cellulosics, and is corrosive to selected metals, such as copper. Organic-solvent-based adhesives are suitable for application on hydrophobic surfaces and are compatible with most metal surfaces. However, organic solvents have a tendency to attack some plastic foams, whereas water-based adhesives may be suitable for this application.

The performance properties of water-based adhesives can be varied by modifying formulations with various additives. A characteristic specific to water-based latexes is that high-molecular-weight polymers can be dispersed at high solids content while maintaining a fairly low-viscosity liquid phase. These high-molecular-weight polymers lead to improved properties, including an increase in resistance to extreme service conditions. In addition, the crosslinking of many water-based adhesives is a possibility. This results in increased heat, moisture, and stress resistance. The largest application of water-based adhesives is in packaging, followed by construction.

9.6.5 Ultraviolet/Electron-Beam-Cured Adhesives

The rapid conversion of specially formulated, 100% reactive liquids to solids can be accomplished using radiation curing. Potential energy sources include UV, electron beam (EB), visible infrared, and microwave sources. Cured materials are used as coatings, inks, adhesives, sealants, and potting compounds.

The UV curing process typically involves the exposure of a reactive liquid that contains a photoinitiator to UV radiation at a wavelength between 200 and 400 nm. The liquid is rapidly converted to a solid, usually in <60 s. In the EB curing process, electrons are artificially generated and accelerated to energies of <100 keV to >1 billion keV. Generally, 50 to 350 keV of electrons are used to cure adhesives having a 25 to 38 μm (1 to 15 mil) bond line. The reactive liquid in the EB process does not contain a photoinitiator. Because the main advantage of UV/EB-curable adhesives is rapid curing at room temperature, they can be used to bond heat-sensitive substrates, such as polyvinyl chloride. In addition, the rapid cure often eliminates the need to fixture parts and greatly increases production rates.

UV/EB-cured adhesives have been used to replace solvent-based adhesives because of the increasing cost of properly recovering and disposing of solvents. Most adhesives, being single-component materials, require no mixing and have little waste. Most UV/EB adhesives are based on an addition polymerization curing mechanism. Materials consist of acrylic acid esters of various forms or combinations of acrylates with aliphatic or aromatic epoxies, urethanes, polyesters, or polyethers. UV/EB adhesives that undergo cationic polymerization are based on epoxies with reactive diluents and cyclic monomers. UV/EB pressure-sensitive adhesives are usually based on acrylics, synthetic rubbers, and/or silicones. Acrylics are the sole or major components. The crosslinked nature of UV/EB-cured adhesives results in good chemical, heat, and abrasion resistance, toughness, dimensional stability, and adhesion to many substrates. Unlike thermal curing, EB curing can be selective, and the depth of penetration can be controlled.

There are several limitations to the use of UV/EB-cured adhesives. EB equipment is expensive, costing as much as $400,000 to $800,000 including accessories. UV equipment is less expensive, but the materials themselves are usually more costly because of the presence of photoinitiators. To cure adhesives properly, either one substrate must be transparent to the UV radiation, or a dual-curing adhesive must be used. Dual-curing adhesives are quickly set by a UV cure and are more fully cured by a second mechanism involving the introduction of heat or moisture or the elimination of oxygen (anaerobics). In EB-curable adhesives, the depth of EB penetration is limited by the density of the material rather than its opacity.

9.7 Adhesive Bonding Process

Some general guidelines for adhesive bonding are (Ref 9.2):

- When received, the adhesive should be tested for compliance with the material specification. This may include both physical and chemical tests.
- The adhesive should be stored at the recommended temperature.
- Cold adhesive should always be warmed to room temperature in a sealed container.
- Liquid mixes should be degassed, if possible, to remove entrained air.
- Adhesives that evolve volatiles during cure should be avoided.
- The humidity in the lay-up area should be <40% relative humidity for most formulations. Lay-up room humidity can be absorbed by the adhesive and is released later during heat cure as steam, yielding porous bond lines and possibly interfering with the cure chemistry.
- Surface preparation is absolutely critical and should be conducted carefully.
- The recommended pressure and the proper alignment fixtures should be used. The bonding pressure should be great enough to ensure that the adherends are in intimate contact with each other during cure.
- The use of a vacuum as the method of applying pressure should be avoided whenever possible, since an active vacuum on the adhesive during cure can lead to porosity or voids in the cured bond line.
- Heat curing systems are almost always preferred because they yield bonds that have a better combination of strength and resistance to heat and humidity.
- When curing for a second time, such as during repairs, the temperature should be at least 50°F below the earlier cure temperature. If this is not possible, then a proper and accurate bond form must be used to maintain all parts in proper alignment and under pressure during the second cure cycle.
- Process control specimens should always be made for testing. These are test specimens that duplicate the adherends to be bonded in material and joint design. The specimen surfaces are prepared by the same method and at the same time as the basic joint. Specimens are also bonded together at the same time with the same adhesive lot used in the basic joint and subjected to the same curing process simultaneously with the basic bond. Ideally, traveler coupons are cut from the basic part, on which extensions have been provided.
- The exposed edges of the bond joint should be protected with an appropriate sealer, such as an elastomeric sealant or paint.

The basic steps in the adhesive bonding process are:

1. Procure and store adhesive.
2. Collect all the parts in the bonded assembly and store them as kits.
3. Verify the fit to bond line tolerances.
4. Clean the parts to promote good adhesion.

5. Mix and/or prepare adhesive.
6. Apply adhesive.
7. Mate the parts and adhesive to form the assembly.
8. Apply a force to produce a good fit.
9. Apply force (concurrent with application of heat to the adhesive to promote a chemical reaction, if needed) to cure or set the adhesive.
10. Inspect the bonded assembly

9.7.1 Storage and Handling of Adhesives

Reactive adhesives have finite lives in storage. Once the materials are compounded, their useful lives are limited. Shelf lives can vary from a few days to >1 year, depending on the basic nature of the materials from which the adhesives are made and the manner in which they are handled. Because of the limited-life nature of these materials, provisions for the storage and handling of inventories are required to ensure the existence of adequate supplies of material in good condition. Information on the shelf life and storage requirements for any material is available from its manufacturer. Manufacturer recommendations should provide the basis for determining the storage facilities and requirements for the intended use.

Generally, the two-component reactive adhesives have much longer shelf lives or use times and are storable for longer times. One-part materials generally require storage at temperatures near –18 °C (0 °F) if they are to be kept for as long as 6 months. For short-term storage, 5 °C (40 °F) will usually suffice. Ambient-temperature storage is possible for many two-part systems, but controlled storage at 5 °C (40 °F) is safer. Ambient- or room-temperature storage may be quite safe for many multicomponent formulations. However, because the term *room temperature* does not specify a definite temperature, it is safer to use refrigerated storage. With refrigeration, the temperature variation is smaller, and the temperature can be controlled and recorded for proof of proper storage conditions. Three levels of storage temperature are common: room temperature (15 to 27 °C, or 60 to 80 °F), refrigerated (2 to 5 °C, or 35 to 40 °F), and frozen (at or below –18 °C, or 0 °F). Some products are specifically designed to have long storage lives in exposed outdoor environments.

As-purchased reactive adhesives are affected by temperature and humidity, and some even by light. These effects are always detrimental; the rate of deterioration depends on the type of base resin and on the form of the material chosen. Adhesives aging in an environment that hastens their deterioration will develop certain characteristics, such as an increase in viscosity or, for films, a loss of tack and drapeability. Brittleness and cracking of the uncured films will start to occur. If the adhesive is subjected to elevated temperatures during its cure cycle, less flow is likely to occur during cure. Gel times of epoxy film adhesives become shorter. If high levels of humidity are also present, the materials can absorb moisture, which will affect their performance when cured.

Extended exposure of the uncured material to temperatures and humidities above those recommended by the manufacturer will reduce its cohesive and adhesive strength when cured, as shown for the epoxy adhesive in Fig. 9.11. Surface effects, such as feathering and crazing, may be evident on the bonded substrates. All these factors contribute to reduced performance and premature failure of the adhesive bonded joint.

9.7.2 Handling Considerations

Reactive adhesives must be stored in sealed containers for any period of time longer than a day or two at room temperature. Otherwise, moisture absorption can be a problem. It is also important to reseal bags of adhesive films before they are refrigerated or frozen. A material is most vulnerable to moisture collection when it is removed from cold storage and the package or container is not properly sealed. Moisture condenses on the adhesive and quickly reduces its mechanical capabilities.

Safety is another consideration when handling resins, hardeners, films, solvents, and other materials. Cotton, leather, or rubber gloves should be worn to protect the hands from repeated contact with the materials. There is not much acute danger with many of these systems, but repeated contact over long periods of time can sensitize the skin and produce unpleasant reactions such as itchiness, redness, swelling, and blisters.

The safe storage of adhesives containing flammable, corrosive, or hazardous substances is of major importance. Many organic solvents used in liquid adhesives are flammable. Some combustible materials have low flash points. These hazardous materials need to be stored in metal cabinet

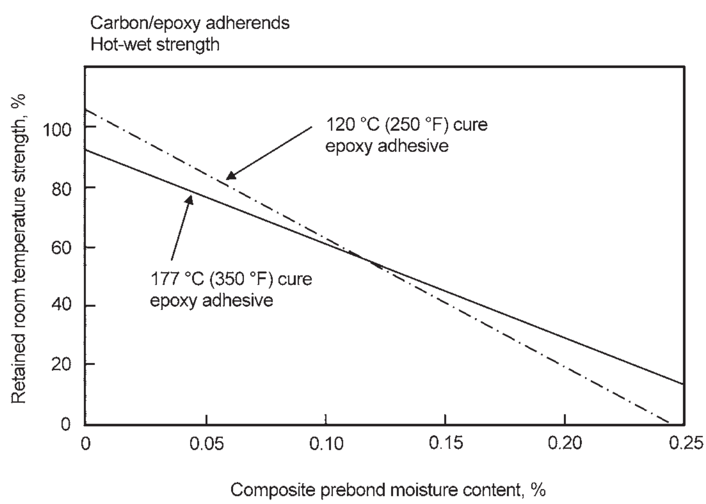


Fig. 9.11 The deleterious effect of prebond moisture on resultant epoxy adhesive bond strength. Source: Ref 9.2

enclosures that provide both isolation and protection. In addition, the areas or enclosures can be equipped with sprinklers for fire suppression. Some adhesive products contain corrosive compounds that require special containers and need to be separated from other materials to avoid interaction. In two-part adhesives, some amine hardeners are considered corrosives, as are anhydride hardeners. Plastic high-density polyethylene containers or containers with an inside phenolic coating are used often with these materials. Drums of corrosives and other hardeners should be stored separately from adhesive film and resins, because a spill or leakage of these products could produce an uncontrolled polymerization reaction, producing excessive heat and possibly toxic fumes.

9.7.3 Kitting of Adherends

Many reactive adhesives have a limited working life at room temperature, and adherends, especially metals, can become contaminated by exposure to the environment. Thus, it is normal practice to kit the adherends so that application of the adhesive and buildup of the bonded assemblies can proceed without interruption. The kitting sequence is determined by the product and production rate. Prefitting of the details is also useful in determining locations of potential mismatch such as high and low spots. A prefit check fixture is often used for complex assemblies containing multiple parts. This fixture simulates the bond by locating the various parts in their exact relationship to one another, as they will appear in the actual bonded assembly. Prefitting is usually conducted before cleaning so that the details can be reworked if necessary.

9.7.4 Prefit Evaluation

For complex assemblies, a prefit evaluation is frequently conducted. The bond-line thickness is simulated by placing a vinyl plastic film (e.g., Verifilm), or the actual adhesive encased in plastic film, in the bond lines. The assembly is then subjected to the heat and pressure normally used for curing. The parts are disassembled, and the vinyl film or cured adhesive is then visually or dimensionally evaluated to see what corrections are required. These corrections can include sanding the parts to provide more clearance, reforming metal parts to close gaps, or applying additional adhesive (within permissible limits) to particular locations in the bond line. Verification of bond-line thickness may not be required for all applications. However, the technique can be used to validate the fit of the mating parts before the start of production, or to determine why large voids are produced in repetitive parts. Once the fit of mating parts has been evaluated, any necessary corrections can be made. For cases in which the component parts can be dimensionally corrected, it is much more efficient to make the correction than risk having to scrap the bonded assembly or, worse yet, having it fail in service.

9.7.5 Surface Preparation for Metal Adherends

Surface preparation is essential for the successful implementation of adhesive bonding technology. Both the initial bond strength and the subsequent bond durability are critically dependent on the interaction between the adhesive (and/or primer) and a pretreated adherend surface.

Structural bonding with paste and film adhesives usually uses a form of chemical surface treatment followed by an adhesive priming operation. This type of treatment is very reliable in its ability to provide a good bonding surface for the adhesive. The chemical processing methods provide a microscopically rough surface for the interface of adhesive molecules. Surface preparation techniques for aluminum adherends consist of either etching or anodizing in acid solutions. These techniques result in microscopically rough adherend morphologies, which have been shown to produce the best bond durability.

Because metallic cleaning is such a critical step, dedicated processing lines are normally constructed, and chemical controls, as well as periodic lap shear cleaning control specimens, are employed to ensure in-process control. Automated overhead conveyances are used to transport the parts from tank to tank under computer-controlled cycles to ensure the proper processing time in each tank.

Aluminum Adherends. The three most prevalent commercial processes used for aluminum alloys are the Forest Products Laboratory (FPL) chromic-sulfuric acid etch, phosphoric acid anodizing (PAA), and chromic acid anodizing (CAA). The FPL chromic-sulfuric acid etch is one of the earliest of the modern methods developed for aluminum surface preparation. The PAA process was developed by the Boeing Company in the late 1960s and early 1970s to improve the durability of bonded structures. Bonds formed with PAA-treated adherends exhibit superior durability during exposure to humid environments compared with those formed with the FPL process. In addition, PAA bonds are less sensitive than FPL bonds to process variables, such as rinse water chemistry and time before rinsing. The PAA oxide has a high degree of microscopic roughness (Fig. 9.12). The oxide consists of a well-developed network of pores on top of a barrier layer. Whiskers protrude from the pores away from the alloy adherend. The total oxide thickness is approximately 400 nm. This degree of microscopic roughness provides sites for mechanical interlocking for improved bond strength and durability. Low-viscosity primers can flow and penetrate into the oxide. The CAA process, although not as popular as the FPL and PAA processes in the United States, has been extensively developed and is widely used in Europe. One advantage of the CAA process is that the oxide is more robust and not as susceptible to damage.

The processing steps for the PAA process are:

1. Vapor degrease by immersing in 1,1,1-trichloroethane at 74 to 78 °C (165 to 172 °F).

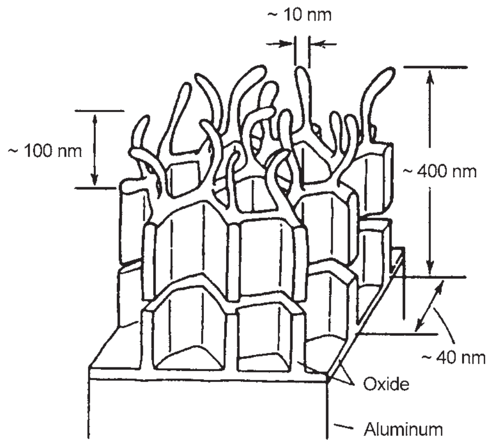


Fig. 9.12 Surface morphology of phosphoric acid anodizing. Source: Ref 9.2

2. Alkaline clean at 66 ± 2 °C (150 ± 5 °F). The alkaline cleaning solution should contain 0.37 to 0.43 lb/gal of TURCO 4215 Special in deionized water plus 0.0075 gal of TURCO 4215 Additive for each pound of TURCO 4215 Special.
3. Deoxidize in the FPL etch solution as a pretreatment by immersion in the solution for 2 to 10 min at 60 to 71 °C (140 to 160 °F). The FPL solution consists of 30 parts by weight (pbw) water, 10 pbw of sulfuric acid (specific gravity 1.83) and 1 to 4 pbw of sodium dichromate. Prior to use, a minimum of 0.25 oz/gal of 2024 aluminum should be dissolved in the solution.
4. Rinse in room temperature tap water.
5. Anodize by applying a dc voltage stepwise to 10 ± 1 V in 2 to 5 min. Maintain at 10 ± 1 V for 20 to 25 min. Turn off the current. The anodizing solution contains 9 fluid ounces of 85% phosphoric acid per gallon of deionized water.
6. Within 2 min after the current has been turned off, immerse the parts into agitated and overflowing clean tap water for 10 to 15 min.

The processing steps for the CAA process are:

1. Vapor degrease using 1,1,1-trichloroethane at 87 to 89 °C (188 to 193 °F).
2. Alkaline clean by immersing in alkaline cleaner at 85 to 91 °C (185 to 196 °F) for 10 min.
3. Rinse in water at room temperature up to 71°C (160°F).
4. Deoxidize by immersion in a solution of 30 pbw water, 10 pbw sulfuric acid (specific gravity, 1.841), and 1 pbw sodium dichromate at 60 to 71°C (140 to 160°F) for 5 to 10 min.
5. Rinse in water at room temperature.

6. Anodize by gently agitating the anodizing solution at 33 to 37 °C (92 to 98 °F) during the anodizing process. The voltage is applied stepwise: (1) apply initial voltage of 5 to 10 V dc; (2) after 2 to 2.5 min, increase by 5 to 10 V at approximately 1 min intervals to 40 ± 2 V; and, (3) then anodize at a final voltage of 40 ± 2 V for 30 to 35 min.
7. Rinse in room temperature water.
8. Seal the surfaces in a solution of 75 to 120 ppm chromic acid in water at 82 to 85 °C (180 to 185°F) for 7 to 9 min. The water pH should be held between 2.5 and 3.8 when checked at 25 °C, (77 °F). The parts are not rinsed following the sealing operation.

Titanium Adherends. As with aluminum, durable surface preparations for Ti-6Al-4V can be achieved by forming oxides in anodizing and/or etching solutions. Typically, anodization results in the best bond durability for titanium alloys, primarily because of the microscopically rough surface morphology that results from the treatment.

One of the most comprehensive investigations into the methods of treating titanium was initiated by the U.S. Naval Air Systems Command in 1978. A team of investigators from the U.S. Naval Air Development Center, the U.S. Army Armament Research and Development Center, and the Martin Marietta Laboratories, working with the cooperation of eight aerospace companies and three adhesive manufacturers, evaluated the leading methods for treating titanium alloys before adhesive bonding. During this investigation, different surface prebond treatments were evaluated. These included the phosphate-fluoride process, modified phosphate fluoride processes, the Dapcotreat process, the dry hone/Pass-Jell 107 process, the Turco 5578 process, the chromic acid anodizing (CAA) process, and the alkaline-peroxide process. The same processes were evaluated for their bondability by using the wedge test per ASTM D3762, and the stress durability test per ASTM D 2919. The results of this testing are summarized in Table 9.5. The CAA process and the liquid hone/Pasa-Jell 107 gave the best results.

Table 9.5 Long-term durability comparison of titanium pretreatments

Rank	Wedge test (1344 h)	Stress durability
1	CA	CA
2	LP }	LP
3	AP }	AP
4	TU	DA
5	DP	TU
6	DA	DP
7	PF	PF
8	PFS	PFS
9	MPFS	MPFS

Abbreviations: AP: alkaline peroxide; CA: chromic acid anodizing; DA: Dapcotreat; DP: dry hone/Pasa-Jell; LP: liquid hone/Pasa-Jell; MPFS: nitric acid/phosphate fluoride stabilized; PF: phosphate fluoride; PFS: phosphate fluoride stabilized; TU: Turco 5578. The bracket indicates treatments are essentially equivalent. Source: Ref. 9.7

The processing steps for the CAA process for titanium are:

1. Vapor degrease in 1,1,1-trichloroethane at 87 to 89 °C (188 to 193 °F).
2. Alkaline clean by immersing in alkaline cleaner at 85 to 91 °C (185 to 196 °F) for 10 min.
3. Rinse in hot water (43 °C, or 110 °F minimum) for at least 5 min.
4. Etch by immersing in the etch solution at room temperature for ½ to 1-½ min. The etch solution is made up of 15% by volume nitric acid (70%) and 3% by volume hydrofluoric acid (50%).
5. Rinse in flowing water for at least 5 min at room temperature.
6. Anodize at 5 to 10 V dc at 1.5 A/ft^2. The anodizing solution is made up of chromic acid (6.0 to 7.5 oz/gal) plus hydrofluoric acid. The hydrofluoric acid is added to obtain a current density of 1.5 A/ft^2. The solution is operated at 16 to 27 °C (60 to 80 °F) during the anodizing process. The voltage should be applied after the parts are immersed in the solution. The voltage is raised to the desired level within 5 min and maintained for 18 to 22 min. The anodized parts should be removed from the solution within 2 min after the current is shut off.
7. Rinse in cold water for 10 to 15 min.
8. Dry the parts thoroughly at 71 °C (160°F) maximum.
9. Adhesive bond or apply primer within 8 h of cleaning.

The processing steps for the Pasa-Jell 107 process are:

1. Solvent wipe to remove all grease and oils.
2. Liquid hone at 40 to 50 psi (276 to 345 kPa) pressure.
3. Alkaline clean in an air-agitated solution maintained at 90 to 100 °C (200 to 212 °F) for 20 to 30 min.
4. Thoroughly rinse in tap water for 3 to 4 min.
5. Etch for 15 to 20 min in a Pasa-Jell 107 solution maintained at <40 °C (100 °F). Pasa-Jell is a proprietary solution containing nitric and hydrofluoric acid.
6. Thoroughly rinse in tap water for 3 to 4 min, then rinse in deionized water for 2 to 4 min.
7. Inspect for a water-break-free surface.
8. Oven dry at 40 to 80 °C (100 to 170 °F) for 30 min minimum.
9. Adhesive bond or apply primer within 8 h of cleaning.

Steel Adherends. Unlike aluminum and titanium, iron does not form coherent, adherent oxides, making it difficult to create a stable film with the fine microscopic roughness needed for good adhesion. Grit blasting is commonly used as a pretreatment, but it is not suitable for cases in which the bonded structure is exposed to severe environments.

The variety and complexity of steel microstructures greatly complicate the task of developing a universal treatment. Although various cleaning treatments and chemical etchants have been used for low-carbon and stainless steels over many years, none has been widely adopted or shown to be superior to grit blasting. One of the main problems with chemical etch treatments of low-carbon steel is the formation of a loosely adhering layer of iron oxide "smut" on the adherend surface. The oxide is difficult to remove before bonding but easily pulls away with the adhesive when the joint is stressed.

Although there is considerable evidence that chemical surface treatments improve the bondability of stainless steels, there is no general agreement on which treatment is best. Either an HNO_3-HF mixture or chromic acid is commonly used as an etchant with stainless steels. A better approach to the formation of durable bonded joints with steels is to use a conversion coating process to deposit a rough, corrosion-resistant layer on the adherend. To achieve such a coating, proprietary zinc and iron phosphate solutions are used to precipitate crystallites onto the steels. However, to achieve this performance, these crystallites must be small. If the grain size is not controlled, the coating becomes so thick that one phosphate crystal precipitates onto another and a weak interface is introduced.

Typical processing steps for conversion coating of steel adherends are:

1. Preclean by grit blasting, grinding, or machining.
2. Alkaline clean for 1 to 5 min at 50 to 75 °C (120 to 165 °F).
3. Water rinse for 1 min at 20 to 25 °C (68 to 77 °F).
4. Grain-refine rinse in titanium/saltwater solution for 0.25 to 1.0 min at 20 to 25 °C (68 to 77 °F).
5. Conversion coat by immersion in coating solution for 1 to 2 min at 40 to 85 °C (105 to 185 °F).
6. Rinse in solution of chromate and water for 0.25 to 1.0 min at 20 to 75 °C (68 to 165 °F).

Copper-Based Alloys. Several etch treatments have been developed for copper and copper alloys that are suitable for long-term structural applications. Two of these, Ebonol C etch and a ferric chlorite/alkaline chlorite etch, result in black oxide surfaces that have microscopically rough morphologies. The processing steps are similar to those used for aluminum and titanium.

The processing steps for Ebonol C, ferric chloride/alkaline chlorite, and ferric chloride/nitric acid etches are shown in Table 9.6. Ebonol C and ferric chloride/alkaline chlorite etches are used for alloys containing at least 95% copper. Both procedures result in a matte black oxide of CuO whose thickness increases linearly with etching time. Ferric chloride/nitric acid etch can be used on other copper alloys.

9.7.6 Priming

Because of the rapid formation of surface oxides on metallic surfaces, the surfaces should be bonded within 8 h of cleaning or primed with a thin protective coating of primer. For parts that will undergo a severe service environment, priming is always recommended, because today's primers contain corrosion-inhibiting compounds (e.g., strontium chromates) that enhance long-term durability (Fig. 9.13). The two critical variables in corrosion of metal bonds are the metal surface preparation treatment and the chemistry of the primer. Some primers contain phenolics, which have been found to produce outstanding bond durability. Once the primer has been cured (e.g., 120 ºC, or 250 ºF), the parts may be stored in an environmentally controlled clean room for quite long periods of time (e.g., up to 50 days or longer would not be unusual).

All cleaned and primed parts should be carefully protected during handling or storage to prevent surface contamination. Normally, clean white cotton gloves are used during handling, and wax-free Kraft paper may be used for wrapping and longer storage. Gloves, which are used to handle

Table 9.6 Etching procedures for copper adherends

Step	Ebonol C	Ferric chloride/alkaline chlorite	Ferric chloride/nitric acid
1. Degrease	Trichloroethane (vapor), 87–90 °C (190–194 °F) as needed	Trichloroethane	Trichloroethane (vapor), 87–90 °C (190–194 °F) as needed
2. Clean	10 vol% HNO_3 (70%), 90 vol% H_2O, 30 s, 25 °C (77 °F)	11 vol% HNO_3, 68 vol% H_3PO_4, 11 vol% acetic anhydride, 10 vol% H_2O, 4 min, 25 °C (77 °F)	—
3. Rinse	H_2O, running transfer to etchant	Distilled H_2O, then acetone	—
4. Etch	Ebonol C, 6.8 kg (240 oz) + H_2O to make 3.8 L (1 gal), 2 min, 36 °C (95 °F)	30 g/L (4 oz/gal) $NaClO_2$, 100 g/L (13 oz/gal) Na_3PO_4, 50 g/L (6.6 oz/gal) NaOH, 15 min, 95 °C (205 °F)	6 wt% FecL (42%); 12 wt% HNO_3, 82 wt% deionized H_2O, 2 min, 25 °C, (77 °F)
5. Rinse	H_2O, 2–3 min, 1–15 °C (50–60 °F)	Deionized H_2O, 25 °C (77 °F), then acetone	H_2O, 3–5 min, 10–15 °C (50–60 °F)
6. Dry	Air or dry N_2	Air	Air or dry N_2

Source: Ref. 9.8

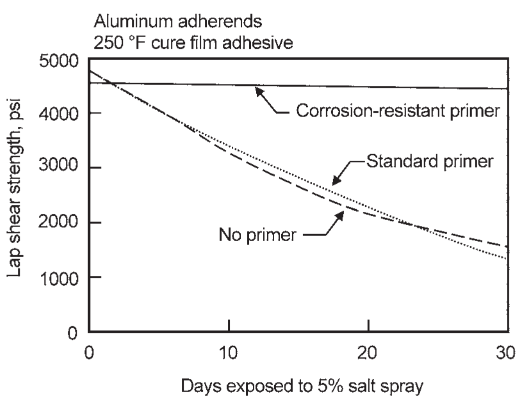


Fig. 9.13 Effect of primers on bond durability of aluminum adherends bonded with an epoxy adhesive. Source: Ref 9.2

cleaned and/or primed adherends, should be tested to ensure that they do not contain silicones or hydrocarbons, which can contaminate the bond line, or sulfur, which can inhibit the cure of the adhesive.

9.7.7 Adhesive Application

In general, the adhesive should be stored according to the manufacturer's recommended procedure. Reactive film adhesives normally require storage at –18 ºC (0 °F) or lower. Two-part reactive adhesives are frequently either stored at room temperature or refrigerated at around 4.4 ºC (40 °F). When an adhesive is removed from cold storage, it is important to allow it to come to room temperature before opening; otherwise, there is the danger that moisture condensation will form on the adhesive, with the potential of either inhibiting proper curing or creating voids when the moisture boils during elevated temperature curing. Film adhesives should be handled and applied in a temperature- and humidity-controlled clean room.

The most commonly used adhesives are supplied as liquids, pastes, or prefabricated films. The liquid and paste systems may be supplied as one-part or two-part systems. The two-part systems must be mixed before use and thus require scales and a mixer. The amount of material to be mixed should be limited to the amount needed to accomplish the task. The larger the mass, the shorter the pot life or working life of the mixed adhesive. To prevent potential exotherm conditions, excess mixed material should be removed from the container and spread out in a thin film. This will prevent the risk of mass related heat buildup and the possibility of a fire or the release of toxic fumes.

One factor that must be considered in adhesive application is the time interval between adhesive preparation and final assembly of the adherend. This factor, which is referred to as pot life, open life, out-time life, or working life, must be matched to the production rate. Obviously, materials that are ready to bond quickly are needed for high-rate applications, such as those found in the automotive and appliance industries. Many two-part reactive systems that cure by chemical reaction often have a limited working life before they become too viscous to apply. Application of liquid adhesives can be accomplished using brushes, rollers, manual sprays, or robotically controlled sprays. Application of paste adhesives can be accomplished by brush, by spreading with a grooved tool, or by extrusion from cartridges or sealed containers using compressed air.

Film adhesives are high quality but costly and thus are used mainly in aircraft applications. They consist of an epoxy, bismaleimide, cyanateester, or polyimide resin film and a fabric carrier. The fabric guarantees a minimum bond-line thickness because it prevents adherends from contacting each other directly. These adhesives are manually cut to size, usually with knives, and placed in the bond lines. When applying film adhesives, it is important to prevent or eliminate entrapped air pockets between the adherend and adhesive film by pricking bubbles or "porcupine" rolling over the adhesive before application.

9.7.8 Bond-Line Thickness Control

Controlling the thickness of the adhesive bond line is an important factor in bond strength. This control can be obtained by matching the quantity of available adhesive to the size of the gap between the mating surfaces under actual bonding conditions (heat and pressure). For liquid and paste adhesives, it is a common practice to embed nylon or polyester fibers in the adhesive to prevent adhesive-starved bond lines. Applied loads during bonding tend to reduce bond-line thickness. A slight overfill is usually desired to ensure that the gap is totally filled. Conversely, if all of the adhesive is squeezed out of a local area due to a high spot in one of the adherends, a disbond can result.

For highly loaded bond lines and large structures, film adhesives are used that contain a calendared film with a thin fabric layer. The fabric maintains the bond-line thickness by preventing contact between the adherends. In addition, the carrier acts as a corrosion barrier between carbon composite skins and aluminum honeycomb core. In the most common case, the bond-line thickness can vary from 0.05 to 0.25 mm (0.002 to 0.010 in.). Extra adhesive can be used to handle up 0.51 mm (0.020 in.) gaps. Larger gaps must be accommodated by reworking the parts or by producing hard shims to bring the parts within tolerance.

9.7.9 Bonding

Theoretically, only contact pressure is required so that the adhesive will flow and wet the surface during cure. In reality, somewhat higher pressures are usually required to (a) squeeze out excess adhesive to provide the desired bond-line thickness, and/or (b) provide sufficient force to ensure all of the interfaces obtain intimate contact during cure.

The position of the adherends must be maintained during cure. Slippage of one of the adherends before the adhesive gels will result in the need for costly reworking, or the entire assembly might be scrapped. When a paste or liquid adhesive is used, it is usually helpful apply a load to the joint to deform the adhesive to fill the bond line. C-clamps, spring loaded clamps, shot bags, and jack screws are frequently used for simple configurations. However, if elevated temperature curing is required, some care is required that these pressure devices do not become heat sinks.

Liquid and paste adhesives that are cured at room temperature will normally develop enough strength after 24 h that the pressure can be removed. For these adhesives that require moderate cure temperatures (e.g., 82 ºC, or 180 ºF), heat lamps or ovens are frequently used. When using heat lamps, some degree of caution is necessary to ensure that the part does not get locally overheated. If the contour is complex, it may be necessary to bag the part and employ the isostatic pressure of an autoclave. Instead of using the positive pressure of a vented bag in an autoclave, a vacuum bag (< 100 kPa, or 15 psia) in an oven is quite commonly used. The disadvantage of this process is that the vacuum tends to cause many adhesives to release volatiles and form porous and weak bond lines.

When film adhesives cured at elevated temperatures (e.g. 120–177 ºC, or 250–350 ºF) are used, autoclave pressures of 100–344 kPa (15–50 psi) are normally used to force the adherends together. Most of these adhesive systems cure in 1 to 2 h at elevated temperature. Autoclave-bonded parts generally require a tool or fixture to hold the parts in place during cure. To provide autoclave pressure, a thin vacuum bag is then sealed over the part. Both straight heat-up and ramped (intermediate hold) cure cycles are used. A typical autoclave cure cycle for a 177 ºC (350 ºF) curing epoxy film adhesive would be:

1. Pull 500 to 740 mm (20 to 29 in.) of Hg vacuum on the assembly and check for leaks. If the assembly contains a honeycomb core, do not pull more than 200 to 250 mm (8 to 10 in.) of Hg vacuum.
2. Apply autoclave pressure, usually in the range of 100 to 340 kPa (15 to 50 psi). Vent the bag to atmosphere when the pressure reaches 100 kPa (15 psi).
3. Heat to 177 ºC (350 ºF) at a rate of 0.5 to 2.8 ºC/min. (1 to 5 ºF/min.). Option: an intermediate hold at 115 ºC (240 ºF) for 30 min is sometimes used to allow the liquid resin to flow and thoroughly wet the adherend surfaces.
4. Cure at 177 ± 5.5 ºC (350 ± 10 ºF) for 1 to 2 h under 100 to 340 kPa (15 to 50 psi).
5. Cool to 65 ºC (150 ºF) before releasing autoclave pressure.

In general, high-performance structural adhesive bonding requires that great care be exercised throughout the bonding process to ensure the quality of the bonded product. Producing durable structural assemblies requires chemical composition control of the adhesive, strict control of surface preparation materials and process parameters, and control of the adhesive lay-up, part fit-up, tooling, and the curing process.

9.7.10 Inspection

One of the main disadvantages of adhesive bonding is that there is no reliable method of nondestructively inspecting a bonded assembly to determine the actual strength of the bond lines. Nondestructive testing will determine only if an interface is present, such as at unbond. Therefore, it is common practice to make and destructively test process control or process control coupons. These should be made at the same time and from the same materials as the actual assembly: the actual adhesives are used, the adherends are cleaned and primed along with the assembly adherends, and they are cured at the same time under the same bag.

ACKNOWLEDGMENTS

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CHAPTER 10

Materials Issues in Joining

A NUMBER OF materials and material combinations are difficult to join, either because of their individual chemical compositions or because of large differences in physical properties between the two materials being joined. In any dissimilar joining process involving high temperatures, differences in the coefficients of thermal expansion (CTEs) are a major consideration. In this chapter, a number of these situations are covered: welding of dissimilar metal combinations; joining of plastics by mechanical fastening, solvent and adhesive bonding, and welding; joining of thermoset and thermoplastic composite materials by mechanical fastening, adhesive bonding, and, for thermoplastic composites, welding; the making of glass-to-metal seals; and joining of oxide and nonoxide ceramics to themselves and to metals by solid-state processes and by brazing.

10.1 Dissimilar Metals Joining

Most combinations of dissimilar metals can be joined by solid-state welding (diffusion welding, explosion welding, friction welding, or ultrasonic welding), brazing, or soldering where alloying between the metals is normally insignificant. In these cases, only the differences in the physical and mechanical properties of the base metals and their influence on the serviceability of the joint should be considered. However, when dissimilar metals are joined by fusion welding processes, alloying between the base metals and a filler metal, when used, becomes a major consideration. The resulting weld metal can behave much differently from one or both base metals during subsequent processing or in service. The principal factors that are responsible for failure (cracking) of dissimilar metal arc welds include general alloying problems (brittle phase formation and limited mutual solubility) of the two metals, widely differing melting temperatures (T_m), CTE differences, and differences in thermal conductivity.

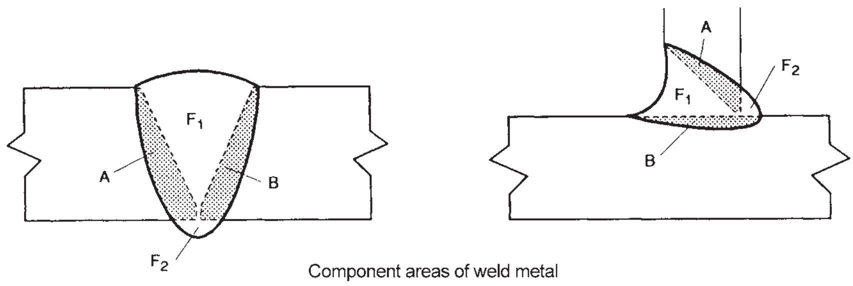
10.1.1 Factors Influencing Joint Integrity

Weld Metal. In the fusion welding of dissimilar-metal joints, the most important consideration is the weld metal composition and properties. Its composition depends on the compositions of the base metals, the filler metal (if used), and the relative dilutions of these. The weld metal composition is usually not uniform, particularly with multipass welds, and a composition gradient is likely to exist in the weld metal adjacent to each base metal. These solidification characteristics of the weld metal are also influenced by the relative dilutions and the composition gradients near each base metal. These characteristics are important with respect to hot cracking of the weld metal during solidification.

The basic concepts of alloying, the metallurgical characteristics of the resultant alloy, and its mechanical and physical properties must be considered when designing a dissimilar-metal joint. For a fusion welding processes it is important to investigate the phase diagram of the two metals involved. If there is mutual solubility of the two metals, the joint can usually be made successfully. If there is little or no solubility between the two metals to be joined, the weld joint will not be successful. The intermetallic compounds that are formed between the dissimilar metals must be investigated to determine their crack sensitivity, ductility, and susceptibility to corrosion. The microstructure of any intermetallic compound is extremely important. In some cases, it is necessary to use a third metal that is soluble with each metal in order to produce a successful joint.

Dilution. In dissimilar-metal welding, the filler metal must alloy readily with the base metals to produce a weld metal that has a continuous, ductile matrix phase. Specifically, the filler metal must be able to accept dilution (alloying) by the base metals without producing a crack-sensitive microstructure. The weld metal microstructure must also be stable under the expected service conditions. A successful weld between dissimilar metals is one that is as strong as the weaker of the two metals being joined, that is, possessing sufficient tensile strength and ductility so that the joint will not fail.

In multipass welding, the composition of each weld bead should be relatively uniform. However, definite compositional differences are likely in succeeding weld beads, especially between a root bead, the beads adjacent to the base metals, and the remaining fill beads. The average composition of the whole weld metal can be calculated when (1) the ratio of the volumes of base metals melted to the entire weld metal volume can be determined, and (2) the compositions of the base and filler metals are known. The dilution can be based on area measurements on a transverse cross section through a test weld. Figure 10.1 illustrates how to deter-



$$\text{Dilution by metal A, \%} = \frac{A}{A + B\,(F_1 + F_2)} \times 100$$

$$\text{Total dilution, \%} = \frac{A + B}{A + B\,(F_1 + F_2)} \times 100$$

$$\text{Dilution by metal B, \%} = \frac{A}{A + B\,(F_1 + F_2)} \times 100$$

Fig. 10.1 Dilution in a dissimilar-metal welded joint. Source: Ref 10.1

mine the dilution by two base metals, A and B, when welding with filler metal F.

The average percentage of a specific alloying element in the diluted weld metal can be calculated using the following equation, developed by the American Welding Society:

$$X_W = (D_A)(X_A) + (D_B)(X_B) + (1 - D_T)(X_F),$$

where X_W is the average percentage of element X in the weld metal; X_A is the percentage of element X in base metal A; X_B is the percentage of element X in base metal B; X_F is the percentage of element X in the filler metal F; D_A is the percent dilution by base metal A, expressed as a decimal; D_B is the percent dilution by base metal B, expressed as a decimal; and D_T is the percent total dilution by base metals A and B, expressed as a decimal.

Melting Temperatures. The difference in melting temperatures (T_m) of the two metals that are to be joined must also be considered. This is of primary interest when a fusion welding process using considerable heat is involved, since one metal may be molten long before the other when subjected to the same heat source. A significant difference between the melting temperatures of the two base metals, or between those of the weld metal and a base metal, can result in rupture of the metal having the lower T_m. Solidification and contraction of the metal with the higher T_m will induce stresses in the other metal while it is in a weak, partially solidified condition. This problem may be solved by depositing one or more layers of a filler metal of intermediate T_m on the face of the base metal with the higher T_m. This procedure is known as buttering. The weld is then made between the buttered face and the other base metal. The buttering layer should serve to reduce the T_m differential. Buttering may also be used to provide a transition between materials with substantially different CTEs but that must endure cycling temperatures in service. Similarly, buttering may be used to provide a barrier layer that will slow the migration of undesirable elements from the base metal to the weld metal during postweld heat treatment (PWHT) or in service at elevated temperatures.

Thermal Conductivity. Most metals and alloys are relatively good conductors of heat, but some are much better than others. Rapid conduction of heat from the molten weld pool by an adjacent base metal may affect the energy input required to locally melt the base metal. When two dissimilar metals of significantly different thermal conductivities are welded together (e.g., plain-carbon steels and copper-base alloys), the welding procedure must provide for this difference. Often the welding heat source must be directed at the metal having the higher thermal conductivity to obtain the proper heat balance.

When welding dissimilar metals, heat loss to the base metals can be balanced somewhat by selectively preheating the metal having the higher thermal conductivity. Dilution is more uniform with balanced heating. Preheating the base metal of higher thermal conductivity also reduces the cooling rate of the weld metal and the heated-affected zone. The net effect of preheating is to reduce the heat required to melt that base metal.

The CTE of the two dissimilar base metals is another important factor. Large differences in CTEs of adjacent metals during cooling will induce tensile stresses in one metal and compressive stresses in the other. The metal subject to tensile stresses may hot crack during welding, or it may cold crack in service unless the stresses are relieved thermally or mechanically. This factor is particularly important in joints that will operate at elevated temperatures in a cyclic temperature mode. Ideally, the CTE of the weld metal should be intermediate between those of the base metals, especially if the difference between those of the two base metals is large. If the difference is small, the weld metal may have a CTE equivalent to that of one of the base metals.

10.1.2 Welding Considerations

The main considerations in welding dissimilar metal combinations include the specific welding process, the process of buttering to reduce weld metal dilution, joint design, and preheat and PWHTs.

Welding Processes. The three most popular arc welding processes utilized for joining dissimilar metals are shielded metal arc welding (SMAW), gas metal arc welding (GMAW), and gas tungsten arc welding (GTAW). Selecting the welding process to make a given dissimilar-metal joint is almost as important as selecting the proper filler metal. The depth of fusion into the base metals and the resulting dilution may vary with different welding processes and techniques. It is not uncommon with SMAW for the filler metal to be diluted up to 30% with the base metal. The amount of dilution can be modified somewhat by adjusting the welding technique. For example, the electrode can be manipulated so that the arc impinges primarily on the previously deposited weld metal. The dilution rate can be kept <25% with this technique. If dilution from one base metal is less detrimental than from the other, the arc should be directed toward that metal. This technique is also applicable to GTAW.

Dilution rates with GMAW can range from 10 to 50%, depending on the type of metal transfer and the welding gun manipulation. Spray transfer gives the greatest dilution, while short-circuiting transfer gives the least dilution. Penetration with submerged arc welding can be greater, depending on polarity, and can result in more dilution. Regardless of the process, dilution is also affected by other factors, including joint design and fit-up. It is always best to have a minimum uniform dilution along the joint. Variations in dilution may produce inconsistent joint properties.

Selection of a suitable filler metal is an important factor in producing a dissimilar-metal joint that will perform well in service. One objective of dissimilar-metal welding is to minimize undesirable metallurgical interactions between the metals. The filler metal should be compatible with both base metals and be capable of being deposited with a minimum of dilution.

Two important criteria that should govern the selection of a proper filler metal for welding two dissimilar metals are that (1) the candidate filler metal must provide the joint design requirements, such as mechanical properties or corrosion resistance, and (2) the candidate filler metal must fulfill the weldability criteria with respect to dilution, T_m, and other physical property requirements of the weldment.

The Schaeffler diagram is commonly used to predict weld metal microstructure and subsequent filler metal selection when joining a stainless steel to a carbon or low-alloy steel. Figure 10.2 illustrates the procedure with an example of a single-pass weld joining mild steel to type 304 stainless steel with ER309 stainless steel filler metal. First, a connecting line is drawn between the two points representing the base metal compositions, based on their chromium and nickel equivalents. Point X, representing the relative dilutions contributed by each base metal, is then located on this line. If the relative dilutions are equal, point X is at the midpoint of the line. A second line is drawn between point X and the point representing the ER309 filler metal composition. The composition of the weld pass lies somewhere on this line, the exact location depending on the total dilution. With 30% dilution, the composition would be at point Y and would be considered acceptable. If a succeeding pass joins the first pass to mild steel, the dilution with the mild steel should be kept to a minimum, to avoid martensite formation in the weld metal.

Buttering. If dilution of austenitic stainless steel filler metal is a problem, it may be controlled by first buttering the joint face of the carbon or low-alloy steel with one or two layers of type 309 or 310 stainless steel filler metal, as shown in Fig. 10.3(a) and (b). After machining and inspecting the buttered layer (Fig. 10.3c), the joint between the stainless steel component and the buttered steel part can be made using conventional welding procedures and the appropriate filler metal for welding the stainless steel base metal (Fig. 10.3d,e). A low-alloy steel component can be heat treated after the buttering operation and then joined to the stainless

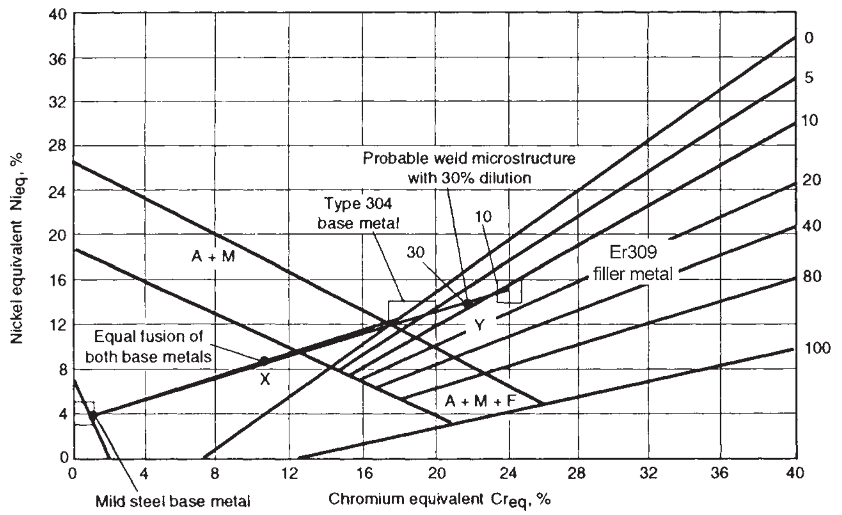


Fig. 10.2 Prediction of weld metal composition from the Schaeffer diagram. A, austenite; F, ferrite; M, martensite. See text for details. Source: Ref 10.1

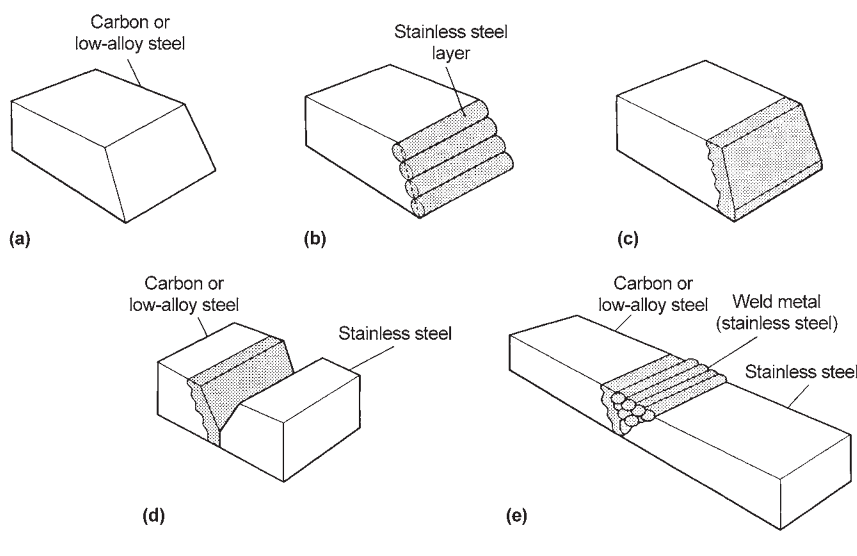


Fig. 10.3 Buttering techniques used to assist welding stainless steel to low-carbon alloy steel: (a) edge prepared for buttering, (b) face buttered with filler metal, (c) buttered face prepared for welding, (d) joint aligned for welding, and (e) joint welded with stainless steel filler metal. Source: Ref 10.1

steel part. This avoids a postweld heat treatment (PWHT) that might sensitize the austenitic stainless steel, potentially resulting in intergranular corrosion.

Joint Design. When designing butt joints between dissimilar metals, consideration must be given to the melting characteristics of each base metal and the filler metal and to dilution effect. Large grooves decrease dilution, permit better control of viscous weld metal, and provide room for better manipulation of the arc for good fusion.

The joint design should provide for appropriate dilution in the first few passes placed in the joint when welding from one side. Improper dilution could result in a layer of weld metal possessing mechanical properties that are inappropriate for the intended service, particularly when the joint will be exposed to cyclic stresses. When welding from both sides, back gouging of the first weld can provide better control of dilution in the first few passes of the second weld.

Dissimilar-metal joints are often made with groove geometries similar to those used in conventional similar-metal welds and are left in the as-welded condition. However, removing the excess penetration of the weld root eliminates possible defects that may be present in the root of the joint, and it eliminates notches and crevices associated with backing rings. Removing the weld root also improves the capabilities of nondestructive tests such as liquid penetrant, radiography, and ultrasonics.

Preheat and Postweld Heat Treatments. The selection of an appropriate preheat or PWHT for a welded joint can present a problem with some dissimilar metal combinations. The appropriate heat treatment for one component of the weldment may be deleterious to the other component for the intended service conditions. For example, if an age-hardenable nickel-chromium alloy is welded to a nonstabilized austenitic stainless steel, exposure of the weldment to the aging treatment for the nickel-chromium alloy would sensitize the stainless steel and decrease its resistance to intergranular corrosion (weld decay). One solution is to use a stabilized austenitic stainless steel if that is acceptable. Another solution might be to butter the face of the age-hardenable, nickel-chromium alloy component with a similar alloy that is not age hardenable. This component is then heat treated to obtain the desired properties. Finally, the buttered surface is welded to the stainless steel component.

10.2 Joining Plastics

In plastic product design, a molded one-piece item is the ideal situation because it eliminates assembly operations. However, mechanical limitations and other considerations often make it necessary to join plastic parts, either to each other or to other plastic or metal parts. In such instances, the joining process can be an efficient production technique if a few precautions are taken and established procedures are followed. The effectiveness of the joining operation can have a large influence on the application of any polymer or composite material. A variety of plastic joining techniques are available as outlined in Fig. 10.4.

Plastic parts can be broadly classified as either thermosets or thermoplastics. Thermosets are low-molecular-weight, low-viscosity monomers that are converted during curing into three-dimensional crosslinked structures that are infusible and insoluble. Crosslinking results from chemical reactions that are driven by heat generated either by the chemical reactions themselves (i.e., exothermic heat of reaction) or by externally supplied heat. As curing progresses, the reactions accelerate and the available volume within the molecular arrangement decreases, resulting in less mobility of the molecules and an increase in viscosity. After the resin gels and forms a rubbery solid, it cannot be remelted. Further heating causes additional crosslinking until the resin is fully cured. Since cure is a thermally driven event requiring chemical reactions, thermosets are characterized as having rather long processing times.

In contrast, thermoplastics are not chemically crosslinked with heat and therefore do not require long cure cycles. They are high-molecular-weight polymers that can be melted, consolidated, and then cooled. They may also be subsequently reheated for forming or joining operations; however, they are inherently high viscosity and have high melting temperatures (T_m). The vast majority of common plastic parts are thermoplastics.

10.2.1 Mechanical Fastening of Plastics

Mechanical fastening can be used to join both similar and dissimilar materials. For example, mechanical fastening is commonly used when

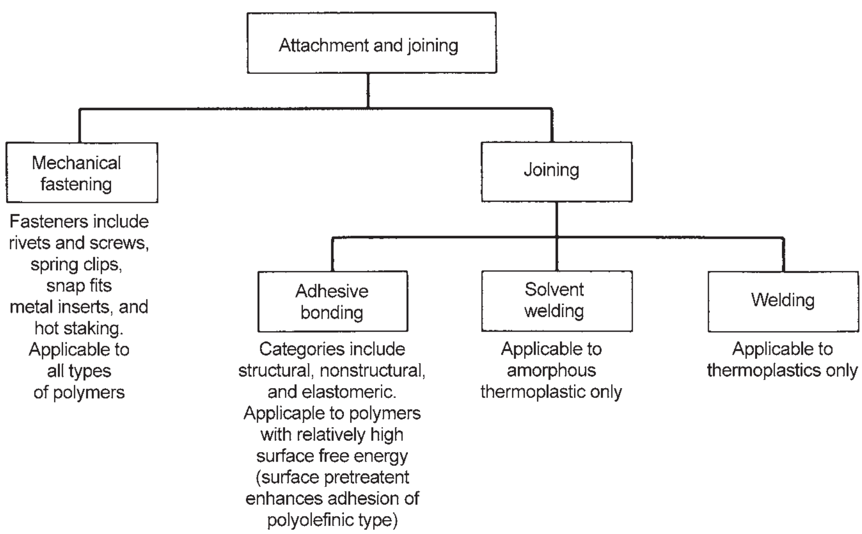


Fig. 10.4 Classification of different plastic joining processes. Source: Ref 10.2

joining a plastic to a metal, either producing permanent joints or allowing disassembly. The advantages of this approach are that no surface treatment is required and disassembly of the components for inspection and repair is straightforward. The main limitations are increased weight, the presence of large stress concentrations around the fastener holes, and potential in-service corrosion problems. The typical applications of mechanical fastening are in the aerospace, automotive, and construction industries.

Machine Screws and Bolts. Thermoplastic resin molded parts are frequently secured together with machine screws or bolts, nuts, and washers (Fig. 10.5a). Particular attention should be paid to the head of the fastener. Conical heads produce undesirable tensile stresses and should not be used. Bolt or screw heads with a flat underside, such as pan heads and round heads, are preferred because the stress produced is spread-out and more uniform. Flat washers are helpful in distributing the assembly force and should be used under both the nut and the fastener head.

Molded-in Threads. When the application involves infrequent assembly, molded-in threads can be used (Fig. 10.5b). Coarse threads can be molded into most materials more easily than fine threads. Threads of 32 or finer pitch should be avoided, along with tapered threads, such as pipe threads, which can cause excessive stress. Other factors that should be considered are:

- If the mating part is metal, overtorquing may result in part failure.
- Feather edges on thread run-outs should be avoided to prevent cross-threading or thread damage.
- The roots and crests of threads should be rounded to reduce stress concentrations as well as to help mold filling.
- Internal threads can be formed by collapsible cores or unscrewing cores. External threads can be formed by split cores or unscrewing devices. All of these increase mold costs.

Self-threading Screws. Self-threading screws are an economical means of securing separable joints in plastic. They can be either thread cutting or thread forming. To select the correct self-threading screw for a job, the designer must know which plastic will be used and its modulus of elasticity. A thread-forming screw displaces material as it is installed in the receiving hole. This type of screw induces high stress levels in the plastic part and is not recommended for parts made of some materials.

Thread-cutting screws, such as type 23, type 25, or one that has a cutting edge on its point, actually remove material as they are installed, avoiding high stress buildup (Fig. 10.5c). However, these screws can cause problems if they are installed and removed repeatedly, because new threads can easily be cut each time they are reinstalled. If repeated assembly is required, type 23 screws should be replaced with a standard machine screw. This cannot be done with a type 25 screw because it has a nonstandard thread pitch.

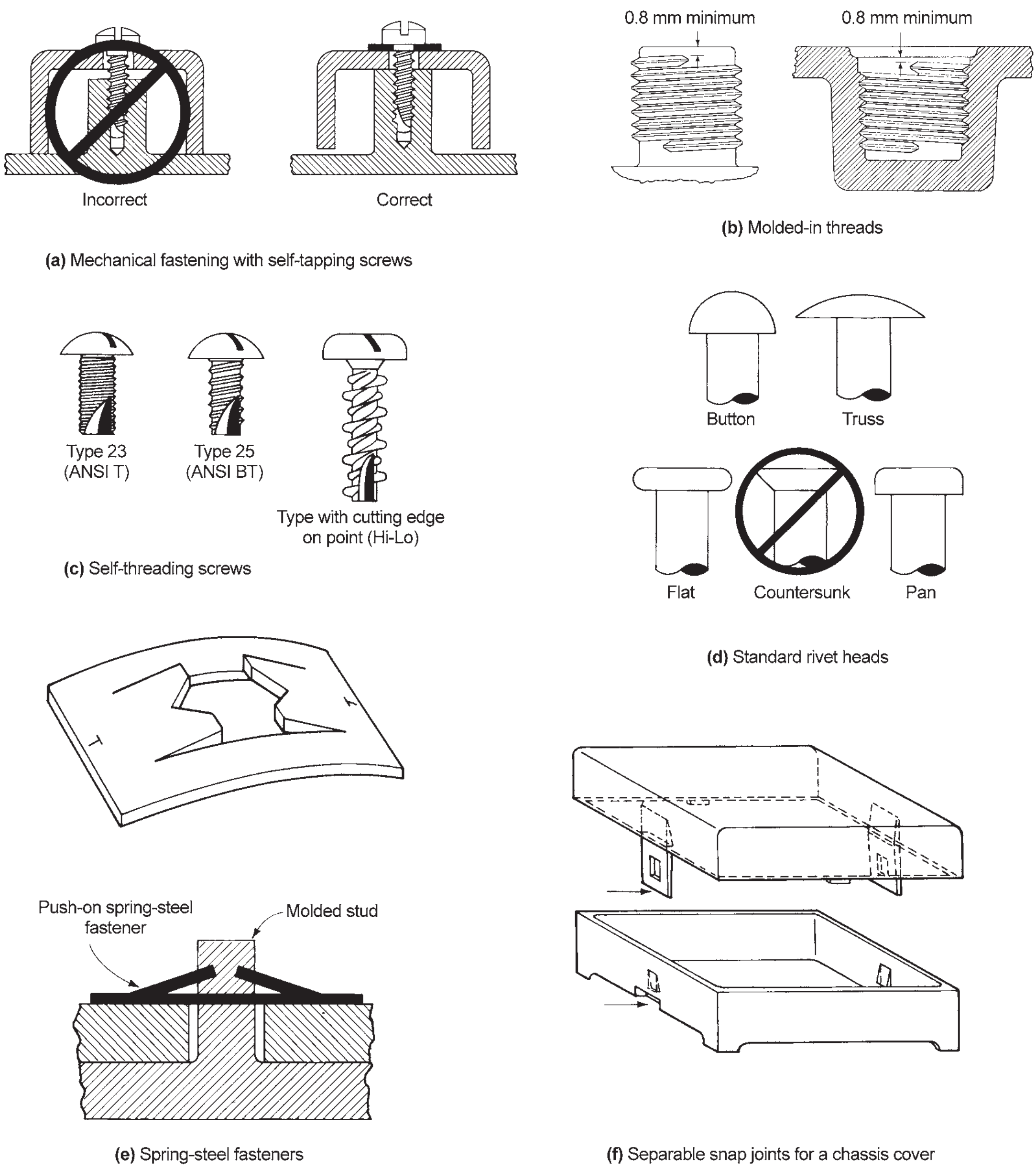


Fig. 10.5 Mechanical joints and fasteners used for plastics. Source: Ref 10.2

Rivets. Rivets are generally used to join thin sheet metal, such as electrical contacts, but they can also be used to join plastic parts. Care must be taken to minimize stresses induced during the fastening operation. To distribute the load, rivets with large heads (three times the shank diameter) should be used with washers under the flared end of the rivet. Standard rivet heads are shown in Fig. 10.5(d). The rivet-setting tool should be calibrated to the correct length to control the compressive stress applied to the joint area.

Spring-Steel Fasteners. In addition to self-locking steel fasteners that replace standard nuts and lock washers, push-on spring-steel fasteners can be used for holding light loads. Spring-steel fasteners are simply pushed over a molded stud (Fig. 10.5e). The stud should have a minimum 0.38 mm (0.015 in.) radius at its base. Too large a radius could create a thick section, resulting in sinks or voids in the molding.

Press Fits. Press fits are occasionally used in thermoplastic applications. Because this joining procedure involves high stresses, the fit must be designed with care. The following points should also be considered: (a) all parts must be clean and free of any foreign substance, (b) press fits of unlike materials should be avoided if the assembly will be subjected to thermal cycling, and (c) press fits should be avoided if the assembly will be subjected to a harsh environment.

Snap Fits. Snap fits are a simple, economical, rapid way of joining components. Many different designs and configurations can be used with this technique. In all types of snap joints, a protruding part of one component, such as a hook, stud, or bead, is briefly deflected during the joining operation and is caught in a depression (undercut) in the mating component (Fig. 10.5f). After the joining operation, the joint should return to a stress-free condition. The joint may be separable or inseparable, depending on the shape of the undercut. The force required to separate the components varies greatly with the design. When designing snap joints, it is particularly important to consider the mechanical load during the assembly operation.

10.2.2 Solvent and Adhesive Bonding of Plastics

Solvent bonding and adhesive bonding are assembly processes in which two or more plastic parts are held together by the action of a separate agent. These techniques have found wide use by virtue of their low cost and adaptability to high-speed production. In addition, solvent and adhesive bonds provide a relatively uniform distribution of stresses over the assembled areas and a high strength-to-weight ratio. Solvent bonding is applicable only for joining of amorphous thermoplastics, whereas adhesive bonding can be used with almost all plastics.

Solvent Bonding. Solvent bonding, also known as solvent cementing and solvent welding, is one of the simplest methods of assembling thermoplastic parts. It is used for many industrial and construction purposes, for example, joining of polyvinyl chloride (PVC) pipe. It is also widely familiar because of its use by hobbyists for building plastic (usually polystyrene) models using solvents such as acetone or toluene. A joint strength of 85 to 100% of that of the parent material can be obtained with solvent bonding.

Solvent bonding can only be used for joining those plastics that can be mildly dissolved using a suitable solvent, which limits its use to amorphous thermoplastics, such as polystyrene, acrylonitrile-butadiene-styrene (ABS), vinyl, acrylic, and polycarbonate (PC). It is not suitable for joining polyethylene (PE), polypropylene (PP), polyamide, polyacetal, polytetrafluoroethylene (PTFE), or most thermosets. For best results, the two plastics being bonded should be identical (e.g., PVC bonded to PVC). Dissimilar plastics can sometimes be bonded if both are compatible with the solvent used.

When a solvent is applied to the surface of a plastic, the solvent dissolves some of the polymer. The polymer becomes "plasticized," or softened, allowing the polymer molecules to move. When two plastic surfaces are prepared with a solvent and then pressed together, the polymer molecules at the two surfaces are able to move across the interface of the surfaces and intertwine with the polymer molecules of the other surface. When the solvent evaporates, the molecules that moved across the interface are frozen or locked into place, thus creating a bond between the two materials.

Fusion time is a function of the evaporation rate of the solvent and may be shortened by heating. However, heating the part is not always recommended because it can cause stress cracking on the surface or bubbling in the solvent layer. Care must be taken not to apply excess solvent, which may degrade the plastic by crazing or cracking its surface beyond the location where bonding is desired.

Three types of solvent materials are commonly used for bonding plastics:

- *Pure solvents* provide the simplest, lowest-cost bond. These include acetone, methylene chloride, toluene, styrene, and methyl ethyl ketone.
- *Doped solvents* (also called solvent cements or bodied cements) contain solutions of the plastic being bonded (generally <15%) to fill gaps in imperfectly fitting parts. Doped solvents are capable of joining more types of materials than solvents alone, and they tolerate larger bondline gaps.
- *Monomer and polymerizing solvents* are doped solvents that also contain catalysts and promoters to produce polymerization at room temperature or at a temperature below the softening point of the plastic. The bonding occurs by polymerization, rather than by solvent evaporation.

Adequate ventilation and attention to fire hazards are required with the use of solvents. Many solvents are classified as volatile organic compounds (VOCs) and may be subject to strict health, safety, and environmental regulations.

The first step in solvent bonding involves preparing the surfaces to be joined. The surfaces must be clean and free of mold-release agents or other contaminants. In some cases, specific surface preparation techniques need to be employed, such as abrading, flame treating, plasma treating, or etching. The application of the solvent to the joint area needs to be accurate and controlled. This can be accomplished by using a brush or syringe applicator. Other application methods include dipping and soak techniques. Once the solvent is applied to the joint, the plastic surfaces soften and become tacky. The areas being joined must have continuous pressure applied to provide a strong bond; however, care should be taken not to apply too much pressure, which can cause part distortion. One day or more at room temperature or several hours at elevated temperature may be needed to cure the bond.

Adhesive Bonding. Adhesive bonding can be used on all types of plastics and can be used to join plastics to other nonplastic materials. Bonding of plastic substrates depends primarily on chemical rather than mechanical adhesion because of the smooth surfaces of most plastic parts. Chapter 9 provides an overview of adhesives technology, including a description of the principal types of adhesives and suitable application techniques.

Surface Preparation of Thermosets. Many parts molded from thermosetting materials have a mold-release agent on the surface that must be removed before adhesive bonding can be accomplished. These agents can usually be removed by washing or wiping with detergent or solvent, followed by light sanding to break the surface glaze. A final solvent wipe also is frequently used. Solvents used for thermosets include acetone, toluene, trichloroethylene, methyl ethyl ketone, low-boiling petroleum ether, and isopropanol. Surface abrasion can be accomplished using fine sandpaper, carborundum or alumina abrasives, metal wools, or steel shot.

Surface Preparation of Thermoplastics. Thermoplastic surfaces, unlike those of thermosets, usually require physical or chemical modification to achieve acceptable bonding. This is especially true of crystalline thermoplastics such as polyolefins, linear polyesters, and fluoropolymers. Surface preparation of plastics before adhesive bonding is critical to bond reliability and integrity. After the surface is cleaned to remove obvious surface contamination, chemical or physical treatments can be used to ensure the complete removal of dirt, oils, and other contaminants. These include solvent cleaning, intermediate cleaning, and chemical treatment.

Solvent cleaning does not chemically or physically alter the surface being cleaned. Solvent cleaning methods include wiping, immersion, spraying, vapor degreasing, and ultrasonic scrubbing. Intermediate cleaning includes any operation that removes surface contaminants by physical, mechanical, or chemical means without chemically altering the adherend surface. Solvent cleaning should always precede intermediate cleaning. Examples of intermediate cleaning procedures include alkaline or detergent cleaning, grit blasting, wire brushing, sanding, and abrasive scrubbing.

Chemical treatment, as the name implies, involves a change in the chemical nature of the adherend surface to improve its adhesion characteristics. Etching promotes adhesion and wettability of polymer adherend surfaces. Depending on the adherend surface and the surface effects desired, a variety of etchants can be used.

Plasma treatment exposures of the polymer surface to a gas plasma generated by glow discharge. This causes atoms to be expelled from the polymer surface, resulting in the formation of a strong, wettable surface with good adhesion characteristics. Adhesive bonds on plasma-treated surfaces can be two to four times stronger than those produced on untreated surfaces.

Priming usually involves the use of dilute adhesive solutions in an organic solvent. These primers are used to enhance wetting, protect the clean adherend surface, serve as a barrier coating to prevent unwanted reactions between adhesive and adherend, and hold adhesive or adherend in place during assembly. Priming generally results in joints with higher reliability and durability.

Selection of Adhesives for Joining Plastics. Selecting the proper adhesive involves consideration of many factors, including manufacturing conditions, substrates involved, joint configuration and size, end-use requirements, and cost. Chapter 9 provides information about the major types of adhesives, adhesive modifiers, applications, and manufacturing uses.

10.2.3 Welding of Plastics

The weldability of plastics depends on whether they are thermosets or thermoplastics. In the case of thermoset resins, a chemical reaction occurs that causes curing, that is, an irreversible crosslinking reaction. Neither molded thermoset or vulcanized elastomer components can be reshaped by means of heating, because degradation occurs. It follows that thermoset and vulcanized rubber components can be joined only with adhesive bonding or mechanical fastening methods. Thermoplastic resins, on the other hand, can be softened as a result of the weakening of secondary van der Waals or hydrogen bonding forces between adjacent polymer chains. Therefore, thermoplastics can be remolded by the application of heat, and they can be fusion welded successfully.

During welding, the glass transition temperature (T_g) in amorphous polymers and the melting temperature (T_m) in crystalline polymers must be exceeded so that the polymer chains can acquire sufficient mobility to interdiffuse. A variety of methods exist for welding thermoplastics and thermoplastic composites (Fig. 10.6). Thermal energy can be delivered externally through conduction, convection, and/or radiation methods or internally through molecular friction caused by mechanical motion at the joint interface. In the case of external heating, the heat source is removed

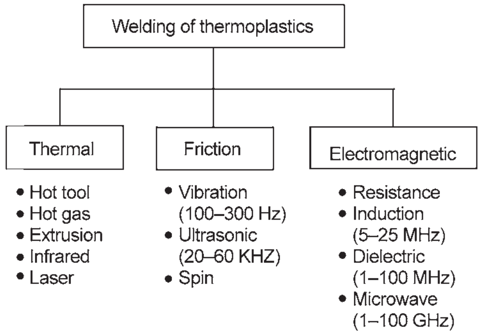


Fig. 10.6 Classification of different welding methods for thermoplastics. Source: Ref 10.2

before the application of pressure, and longer welding times are balanced by the greater tolerance to variations in material characteristics. Internal heating methods depend markedly on the material properties. Heating and pressure are applied simultaneously, and shorter welding times are generally involved during the joining process. Welding is accomplished in stages. During the initial stage, the polymer-chain molecules become mobile and surface rearrangement occurs. This is followed by wetting and the diffusion of polymer chains across the interface. The final stage involves cooling and solidification. Additional information on plastics welding is given in Section 10.3.3, "Joining Thermoplastic Composites."

10.3 Joining Polymer Matrix Composites

Polymeric matrices for advanced composites are classified as either thermosets or thermoplastics. However, in contrast to commodity plastic parts where thermoplastics dominate, the majority of resins used for advanced composites are thermosets. Epoxy-based resins that cure at elevated temperatures are the most widely used for room temperature up to 120 °C (250 °F). For higher-temperature applications up to 177 °C (350 °F), bismaleimide and cyanate esters are available. Finally, polyimide-based resins can withstand temperature in excess of 260 °C (500 °F) for limited amounts of time.

Thermoset composite structures can be joined either by mechanical fastening or by adhesive bonding. Since thermoplastic resins can be reprocessed by heating above their T_m, they can also be joined by a number of welding processes.

10.3.1 Mechanical Fastening of Thermoset Composites

The usual bolts, pins, and blind fasteners are used for composites; however, problems have led to the development of numerous special-purpose fasteners. Some of these problems are drilling of and installation damage to the composite, delamination of the composite material around the hole and pullout of the fastener under load, differences in expansion coefficients of the composite and the fastener, galvanic corrosion between the composite hole wall and the fastener, moisture and fuel leaks around the fastener, and fretting. The load-carrying capability has been significantly improved by increasing the head diameter of fasteners in order to distribute loads over a greater surface area. The bases of nuts and collars were similarly increased. Fasteners for composites should fit the holes with no clearance in order to avoid fretting, but an interference fit may cause delamination. This problem has been alleviated to some extent by the development of several special sleeve/fastener combinations. The extreme temperature changes experienced by aircraft can cause differential thermal expansion and contraction of composites and their fasteners, thus altering clamp-up loads. Therefore, all new joint designs should be thoroughly tested to ensure satisfactory service.

When a hole is placed in a composite laminate, it creates a stress concentration and the overall load bearing capability of the laminate is severely reduced. Even a properly designed mechanically fastened joint exhibits only 20 to 50% of the basic laminate tensile strength. The various failure modes for composite joints are shown in Fig. 10.7. Potential causes for the other failure modes shown include:

- *Bearing:* Bearing failures are characterized by localized damage, such as delaminations and matrix crazing around the hole. Bearing failures occur by the fastener causing localized comparession loading leading to bucking and kinking of the fibers followed by crushing of the matrix.
- *Shear-out:* Insufficient edge distance, or too many plies oriented in the load direction
- *Tension:* Insufficient width, or too few plies oriented in the load direction
- *Cleavage-tension:* Insufficient edge distance and width, or not enough cross-plies (e.g., +45º and –45º)
- *Fastener pull-through:* Countersink too deep, or use of a shear head fastener.
- *Fastener failure:* Fastener too small for laminate thickness, unshimmed gaps or excessive shimmed gaps in joint, or insufficient fastener clamp-up.

Like hole drilling, fastener installation in composites is more difficult and damage prone than for metallic structure. Some of the potential problems with fastener installation are shown in Fig. 10.8. Unshimmed gaps can cause cracking of either the composite skin or the composite substructure (or both) as the fastener is being installed and pulls the two pieces together. In fuel tanks, channel seal grooves are often used to help prevent fuel leakage. In addition, fasteners with O-ring seals can be used to further

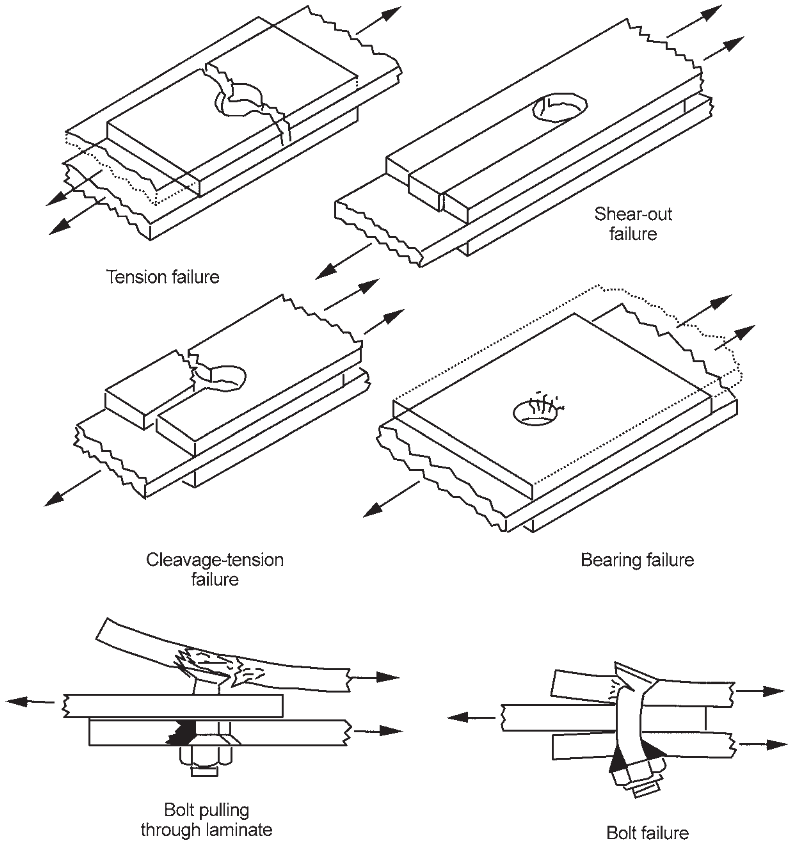


Fig. 10.7 Composite mechanically fastened joint failure modes. Source: Ref 10.3

prevent leakage. Experience has shown that these are potential areas for interlaminar cracking. While good clamp-up of the fastener is certainly desirable, overtorquing fasteners can also result in cracking. If the countersink radius is too small and does not match that of the fastener head-to-shank radius, the fastener can apply a concentrated point load and cause matrix cracking. Likewise, fastener misalignment, where the hole and the countersink are not properly aligned, can result in point loading and cracking. In addition, fastener cocking during loading (Fig. 10.9) can result in point loading and lead to progressive damage during fatigue cycling.

Shimming. Before starting hole drilling and fastener installation, it is important to check all joints for the presence of gaps. The presence of gaps can unnecessarily preload metallic members when fasteners are installed, a condition that can initiate premature fatigue cracking and even stress corrosion cracking of aluminum. However, gaps in structure containing composites can cause even more serious problems than in metallic structure. Because composites do not yield and are more brittle and less forgiving than metals, excessive gaps can result in delaminations when

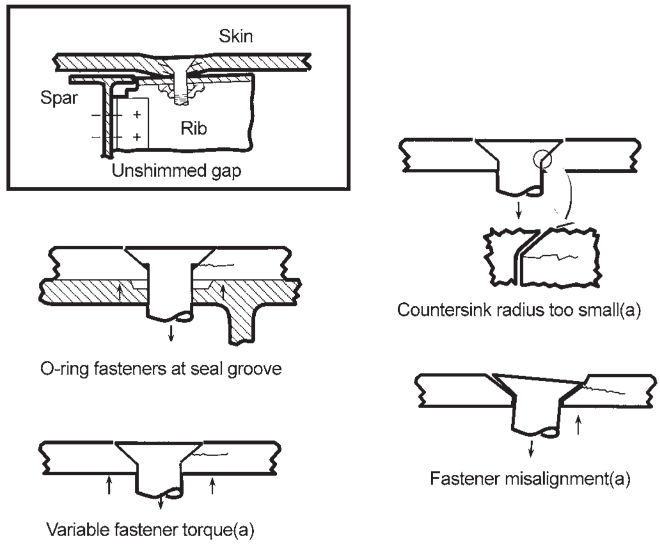


Fig. 10.8 Fastener installation defects in polymer-matrix composites. (a) In conjunction with unshimmed gap conditions. Source: Ref 10.4

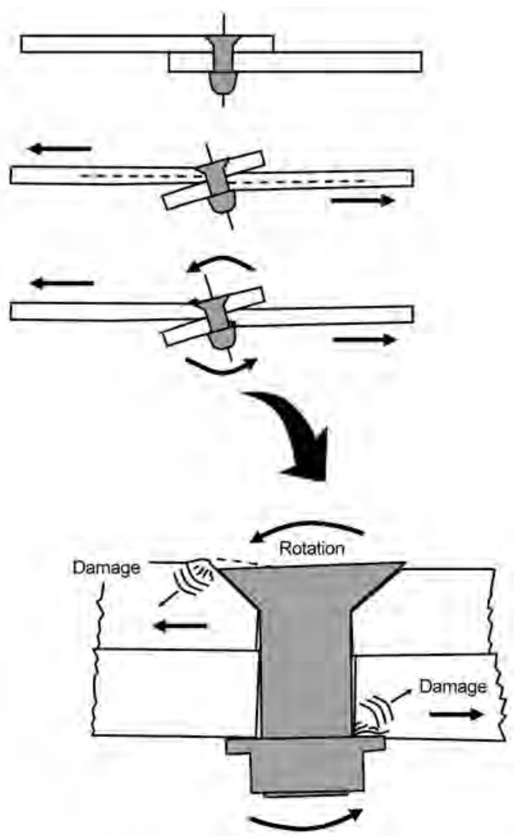


Fig. 10.9 Fastener cocking in single-lap shear joint. Source: Ref 10.3

they are pulled out during fastener installation. The composite is put in bending because of the force exerted by the fastener drawing the parts together and can develop matrix cracks and/or delaminations around the holes. Cracks and delaminations usually occur on multiple layers through the thickness and can adversely affect the joint strength. Gaps can also trap metal chips and contribute to backside hole splintering. If the skin is composite and the substructure is metal, and if an appreciable gap is present during fastener installation, the composite skin will often crack and delaminate. If both the skin and substructure are composite, then cracks can develop in either the skin or substructure, or both. Substructure cracking often occurs at the radius between the top of the stiffener and the web.

To prevent unnecessary preloading of metallic structure, and the possibility of cracking and delaminations in composite structure, it is important to measure all gaps and then shim any gaps >0.13 mm (>0.005 in.). Liquid shims, which are filled thixotropic adhesives, can be used to shim gaps between 0.13 and 0.75 mm (0.005 and 0.030 in.). If the gap exceeds 0.75 mm (0.030 in.), then a solid shim is normally used, but engineering approval is often required for a gap this large. Solid shims can be made from solid metal, laminated metal that can be peeled to the correct thickness, or composite. When selecting a solid shim material, it is important to make sure there is no potential for galvanic corrosion within the joint.

Liquid shimming can be accomplished by first drilling a series of undersize holes in the two mating surfaces, for installing temporary fasteners, to provide a light clamp-up during the shimming process. The liquid shim is usually bonded to one of the two mating surfaces. The surface that will be bonded should be clean and dry, to provide adequate adhesion. Composite surfaces should be scuff sanded. The other surface is covered with release tape or film. After the liquid shim is mixed, it is buttered onto one surface, the other surface is located, and then the joint is clamped up with mold-released temporary fasteners. The excess or squeeze-out is removed before gellation, which usually occurs within an hour of mixing. After the shim material is cured, typically for about 16 h, the part is disassembled and any voids or holes in the shim are repaired. After the repair, the parts are assembled.

Hole Drilling. Hole drilling of composites is more difficult than in metals, because of their relatively low sensitivity to heat damage, and their weakness in the through-the-thickness direction. Composites are very susceptible to surface splintering, particularly if unidirectional material is present on the surface. Note that splintering can occur at both the drill entrance and exit side of the hole. When the drill enters the top surface, it creates peeling forces on the matrix as it grabs the top plies, and when it exits the hole, it induces punching forces that again creates peel forces on the bottom surface plies (Fig. 10.10). If top surface splintering is encountered, it is usually a sign that the feed rate is too fast, while exit surface splintering indicates that the feed force is too high. It is common practice to cure a layer of fabric on both surfaces of composite parts, which will largely eliminate the hole splintering problem; that is, woven cloth is much less susceptible to splintering than unidirectional material. When drilling composites, a backup material such as aluminum or composite, clamped to the backside, will frequently help to prevent backside hole splintering. Since epoxy matrix composites will start to degrade if heated above 205 ºC (400 ºF), it is important that heat generation be minimized during drilling.

While standard twist drills are used for drilling metallic structure, a number of unique drill geometries have been developed for composites (Fig. 10.11). The design of the drill and the drilling procedures are very dependent on the materials being drilled. For example, carbon and aramid fibers exhibit different machining behavior and therefore require different drill geometries and procedures. In addition, composite-to-metal stack-ups will also require different cutters and procedures. The flat two-flute and four-flute dagger drills were developed specifically for drilling stack-ups of carbon/epoxy. When drilling through composite-to-metal stack-ups, the drill geometry is usually controlled more by the metal, and modi-

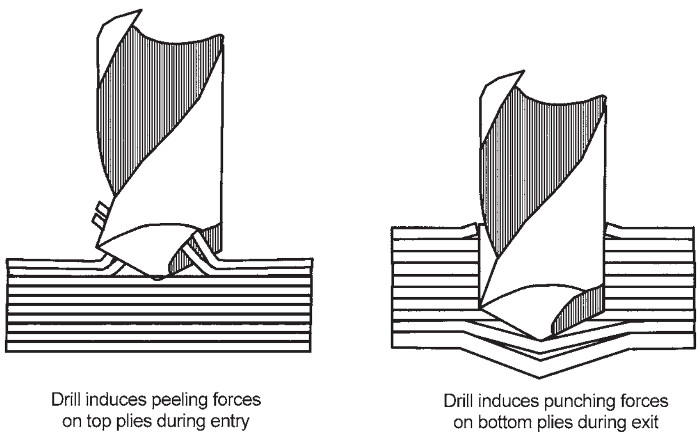


Fig. 10.10 Drilling forces on composite laminate. Source: Ref 10.4

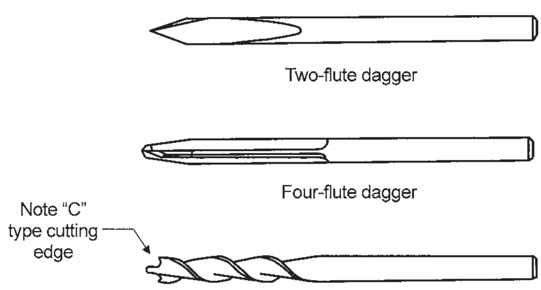


Fig. 10.11 Some composite drill configurations. Source: Ref 10.4

fied twist drill geometries are often used. Because of their low compressive strengths, aramid fibers have a tendency to recede back into the matrix rather than being cleanly cut, resulting in fuzzing and fraying during drilling. Therefore, the aramid drill contains a "C" type cutting edge that grabs the fibers on the outside of the hole and keeps the fibers in tension during the cutting process.

While standard high-speed-steel (HSS) drills work well in glass and aramid composites, the extremely abrasive nature of carbon fibers requires carbide drills to obtain an adequate drill life. For example, an HSS drill may only be capable of drilling one or two acceptable holes in carbon/epoxy, while a carbide drill of the same geometry can easily generate ≥50 acceptable holes.

Fastener Selection. Mechanical fastener material selection for composites is important in preventing potential corrosion problems. Aluminum alloy and cadmium-coated steel fasteners will galvanically corrode when in contact with carbon fibers. Titanium (Ti-6Al-4V) is usually the best fastener material for carbon fiber composites, based on its high strength-to-weight ratio and corrosion resistance. It should be noted that glass and aramid fibers, being nonconductive, do not cause galvanic corrosion with metallic fasteners.

In any mechanically fastened joint, high clamp-up forces are beneficial to both static and fatigue strength. High clamp-up produces friction in the joint, delays fastener cocking and reduces joint movement, or ratcheting, during fatigue loading. Most holes eventually fail in bearing caused by fastener cocking and localized high bearing stresses (Fig. 10.9). To allow the maximum clamp-up in composites without locally crushing the surface, special fasteners have been designed for composites that have large footprints (large heads and nut areas that bear against the composite) to help spread the fastener clamp-up loads over as large an area as possible. Washers are also used under the nut, or collar, to help spread the clamp-up loads. In general, the larger the bearing area, the greater the clamp-up that can be applied to the composite, resulting in improved joint strength. In addition, tension head rather than shear head fasteners are normally used in composites, because they are not as susceptible to bolt bending during fatigue or fastener pull-through during installation in thin structure.

Rivets are rarely used in high-performance composites for two reasons: (1) aluminum rivets will galvanically corrode when in contact with carbon fibers, and (2) the vibration and expansion of the rivet during the driving process can cause delaminations. If rivets are used, they are usually a bimetallic rivet consisting of a Ti-6Al-4V pin with a softer titanium-niobium tail and are installed by squeezing rather than vibration driving. In addition, the head that is upset must be against metallic structure and not composite. There are also hollow-end solid rivets designed to allow flaring of the ends without damaging expansion when used in double countersunk holes in composites.

10.3.2 Adhesive Bonding of Thermoset Composites

Bonding to composites rather than metals introduces significant differences in criteria for adhesive selection for two reasons: (1) composites have lower interlaminar shear stiffness than metals, and (2) composites have much lower shear strengths than metals. (Interlaminar shear stiffness and strength depend on the properties of the matrix, not of the fibers.) The exaggerated deformations in a composite laminate bonded to a metal adherend under shear loading are shown in Fig. 10.12. The composite laminate tends to shear like a deck of cards. The adhesive passes the load from the metal into the composite until, at some distance *L*, the strains in each material are equal. In the composite, the matrix resin acts as an adhesive to pass load from one fiber ply to the next. Because the matrix shear stiffness is low, the composite plies deform unequally in tension. Failure tends to initiate in the composite ply next to the adhesive near the beginning of the joint or in the adhesive in the same neighborhood. The highest failure loads are achieved by an adhesive with a low shear modulus and high strain. Basic design practice for adhesively bonded composite joints should ensure that the surface fibers in a joint are parallel to the load direction (zero degrees) to minimize interlaminar shear, or failure, of the bonded adherend or substrate layer.

Aluminum and titanium are often bonded into composite assemblies. However, solid aluminum adherends should never be hot bonded directly to carbon/epoxy, because the large differences in the coefficients of thermal expansion (CTE) will result in significant residual stresses, and because carbon fiber in contact with aluminum will form a galvanic cell that will corrode the aluminum. Because of the differences in CTE between aluminum and carbon/epoxy, total destruction of bonds between carbon/epoxy and aluminum have been observed on cool down from elevated temperature or on exposure to freezing temperatures.

The selection of an adhesive is often determined by the maximum service temperature. For example, a high-temperature structure fabricated

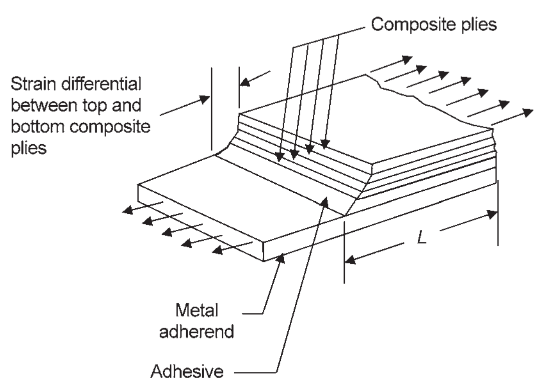


Fig. 10.12 Uneven strain distribution in composite plies. Source: Ref 10.3

from carbon/bismaleimide will normally warrant the use of a compatible bismaleimide adhesive. Film adhesives for epoxy, bismaleimide, cyanate ester, and polyimide structures are available.

Bonded Joint Design. In a structural adhesive joint, the load in one component is transferred through the adhesive layer to another component. The load transfer efficiency depends on the joint design, the adhesive characteristics, and the adhesive/substrate interface. To effectively transfer loads through the adhesive, the substrates (or adherends) are overlapped so that the adhesive is loaded in shear. Typical joint designs are shown in Fig. 10.13. There is a limit to the thickness of the adherends that can be loaded by a single bond line. As the applied loads increase, the thickness of the adherends increases, and eventually one must move from the single-lap to the double-lap and then finally to the cocured double scarf or to a step-lap joint. The effect of joint design with increasing loads is shown in Fig. 10.14. The increase in joint complexity is necessary to ensure that the bond strength is higher than the strength of the increasing adherend thickness.

The load path for a single-lap shear joint is highly eccentric, producing large secondary bending moment resulting in severe peel stresses. Therefore, this type of joint should only be used for very lightly loaded structures or skins that are supported by underlying structure such as an internal frame or stiffener. Normally, single-lap joints should not be considered

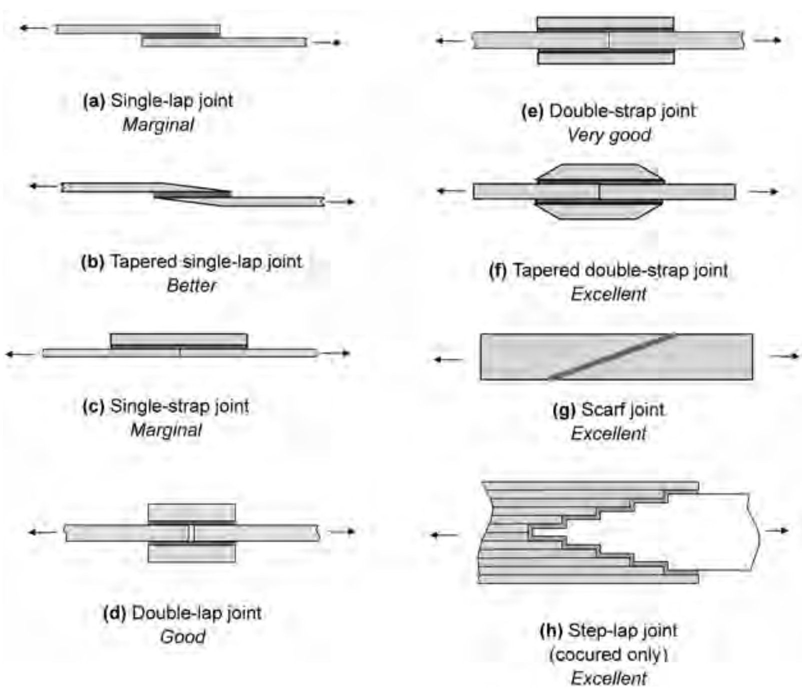


Fig. 10.13 Typical adhesively bonded joint configurations. Source: Ref 10.3

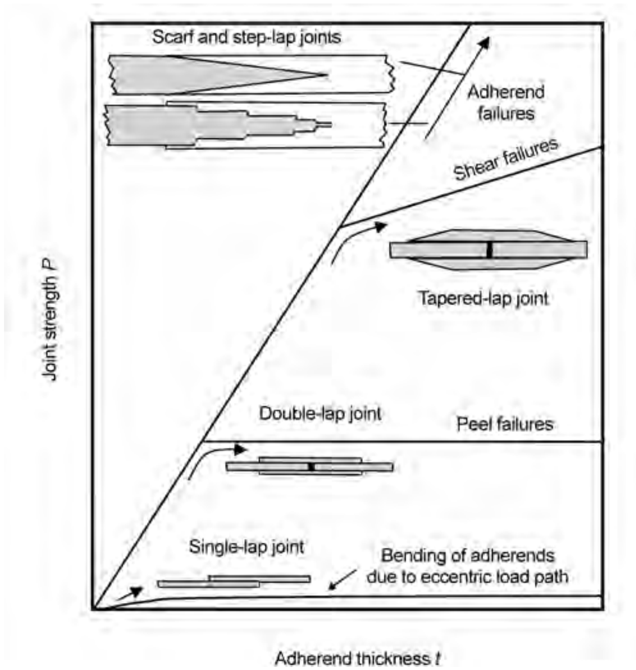


Fig. 10.14 Effect of adherend thickness on failure modes of adhesively bonded joints. Source: Ref 10.3

for joints thicker than about 2 mm (0.07 in.) for quasi-isotropic composite laminates. Although the double-lap joint has no primary bending moment because the resultant load is collinear, peel stresses arise because of the moment produced by the unbalanced shear stresses acting at the ends of the outer adherend. The resulting peel stresses are much smaller than those in single-lap joints; however, they do limit the thickness of the material that can be joined. Tapering the ends of the joint significantly increases the load capability of the double-lap joint (Fig. 10.13f). Since the scarf and step-lap joints develop negligible peel stresses, they can be used to join thicker composite laminates. However, the scarf joint requires a shallow taper angle to effectively transfer the load and thus can result in a very long joint in a thick composite laminate. Therefore, it is rarely used as a primary joining technique. However, it is frequently used for repairing thin skins in honeycomb structures. Although the step-lap joint configuration is difficult to fabricate, it does contain discrete steps that can be used for ply location during fabrication. As a result of these difficulties for both the scarf and step-lap joints, mechanical fastening is probably a more viable option for thick laminates, those thicker than about 3 mm (0.125 in.).

Composite Surface Preparation. The first consideration for preparing a composite part for secondary adhesive bonding is moisture absorption of the laminate itself. Absorbed laminate moisture can diffuse to the surface of the laminate during elevated temperature cure cycles, resulting in weak bonds or porosity or voids in the adhesive bond line and, in extreme cases, where fast heat-up rates are used, actual delaminations within the composite laminate plies. If honeycomb is used in the structure, moisture can turn to steam, resulting in node bond failures or blown core.

Relatively thin composite laminates, ≤3 mm (≤0.125 in.) in thickness, can be effectively dried in an air-circulating oven at 120 ºC (250 °F) for 4 h minimum. Drying cycles for thicker laminates should be developed empirically using the actual adherend thicknesses. After drying, the surface should be prepared for bonding and then the actual bonding operation conducted as soon as possible. It should be noted that prebond thermal cycles, such as those using encapsulated film adhesive to check for part fit-up before actual bonding, can also serve as effective drying cycles for thin sections. In addition, storage of dried details in a temperature- and humidity-controlled lay-up room can extend the time between drying and curing.

Numerous surface preparation techniques are currently used before the adhesive bonding of composites. The success of any technique depends on establishing comprehensive material, process, and quality control specifications and adhering to them strictly. One method that has gained wide acceptance is the use of a peel ply. In this technique, a closely woven nylon or polyester cloth is used as the outer layer of the composite during lay-up and cure. After curing, this ply is torn or peeled away just before bonding or painting. The theory is that the tearing or peeling process fractures the resin matrix coating and exposes a clean, virgin, roughened surface for the bonding process. The surface roughness attained can, to some extent, is determined by the weave characteristics of the peel ply. Some manufacturers advocate that this is sufficient, while others maintain that an additional hand sanding or light grit blasting is required to adequately prepare the surface. The abrasion increases the surface area of the surfaces to be bonded and may remove residual contamination, as well as removing fractured resin left behind from the peel ply. However, the abrading operation should be conducted with care to avoid exposing or rupturing the reinforcing fibers near the surface.

All composite surface treatments should have the following principles in common: (1) the surface should be clean before abrasion to avoid smearing contamination into the surface, (2) the glaze on the matrix surface should be roughened without damaging the reinforcing fibers or forming subsurface cracks in the resin matrix, (3) all residue should be removed from the abraded surface in a dry process (i.e., no solvent), and (4) the prepared surface should be bonded as soon as possible after preparation.

Adhesive Selection. Epoxy-based adhesives are by far the most commonly used materials for bonding or repair of advanced composite structures. Epoxy adhesives impart high-strength bonds and long-term durability over a wide range of temperatures and environments. The ease with which formulations can be modified makes it fairly easy for the epoxy adhesive fabricator to employ various materials to control specific performance properties, such as density, toughness, flow, mix ratio, pot life/shelf life, shop handling characteristics, cure time/temperature, and service temperature.

The room-temperature shear stress/shear strain behaviors of a lower-strength, lower-modulus "ductile" and a higher-strength, higher-modulus "brittle" adhesive are shown in Fig. 10.15. The ductile epoxy-based film adhesives used today for service temperatures up to 120 ºC (250 °F) are toughened by the addition of rubber, nylon, or vinyl additives. Since the addition of these tougheners lowers the glass transition temperature (T_g), epoxy adhesives intended for higher usage temperatures are generally untoughened. This increases their elevated temperature resistance but also reduces their room-temperature peel resistance. While the brittle high-strength adhesive has the highest strength, the tough ductile adhesive, which has a much larger area under the shear stress/strain curve, would be a much more forgiving adhesive, particularly in structural joints that can experience peel and bending loads. However, even the brittle adhesives exhibit substantial ductility when tested at elevated temperatures approaching their upper use service temperatures.

Bismaleimide and polyimide adhesives have even higher service temperatures but are in general not as strong or as tough as the lower-temperature epoxy adhesives. This being said, there are some formulations of both bismaleimide and cyanate ester adhesives that are toughened with thermoplastic additions with only a moderate reduction in upper usage temperature.

10.3.3 Joining Thermoplastic Composites

A unique advantage of thermoplastic composites is the many joining options available. While thermosets are restricted to adhesive bonding and

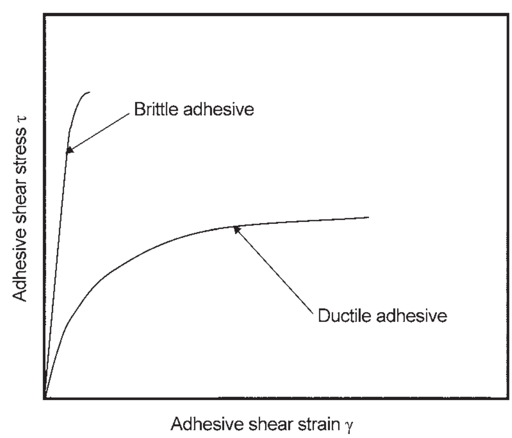


Fig. 10.15 Typical stress-strain behavior for brittle and ductile adhesives. Source: Ref 10.3

mechanical fastening, thermoplastic composites can be joined by melt fusion, dual resin bonding, resistance welding, ultrasonic welding, or induction welding, as well as by conventional adhesive bonding and mechanical fastening.

Adhesive Bonding. In general, structural bonds using thermoset (e.g., epoxy) adhesives produce lower bond strengths with thermoplastic composites than with thermoset composites. This is believed to be due primarily to the differences in surface chemistry between thermosets and thermoplastics. Thermoplastics contain rather inert, nonpolar surfaces that impede the ability of the adhesive to wet the surface. A number of different surface preparations have been evaluated, including sodium hydroxide etching, grit blasting, acid etching, plasma treatments, silane coupling agents, corona discharge, and Kevlar (aramid) peel plies. While a number of these surface preparations, or combinations of them, give acceptable bond strengths, the long-term service durability of thermoplastic adhesively bonded joints has not yet been established.

Mechanical Fastening. Thermoplastic composites can be mechanically fastened in the same manner as thermoset composites. Initially, there was concern that thermoplastics would creep excessively, resulting in a loss of fastener preload and thus lower joint strengths. Extensive testing has shown that this was an unfounded fear and that mechanically fastened thermoplastic composite joints behave very similarly to thermoset composite joints.

Melt Fusion. Since thermoplastics can be processed multiple times by heating above their T_g for amorphous resins or above their melting temperature (T_m) for semicrystalline resins with minimal degradation, melt fusion essentially produces joints as strong as those of the parent resin. An extra layer of neat (unreinforced) resin film can be placed in the bond line to fill gaps and to ensure that there is adequate resin to facilitate a good bond. However, if the joint is produced in a local area, adequate pressure must be provided over the heat-affected zone to prevent the elasticity of the fiber bed from producing delaminations at the ply interfaces.

Dual Resin Bonding. In this method, a thermoplastic film with a lower T_m is placed at the interfaces of the joint to be bonded. In a process called amorphous bonding or the Thermabond process, a layer of amorphous polyetherimide (PEI) is used to bond two polyetheretherketone (PEEK) composite laminates together (Fig. 10.16). To provide the best bond strengths, a layer of PEI is fused to both PEEK laminate surfaces before bonding to enhance resin mixing. In addition, an extra layer of film may be used at the interfaces for gap-filling purposes. Since the processing temperature for PEI is below the T_m of the PEEK laminates, the danger of ply delamination within the PEEK substrates is avoided. Like the melt fusion process, dual resin bonding is normally used to join large sections together, such as bonding stringers to skins.

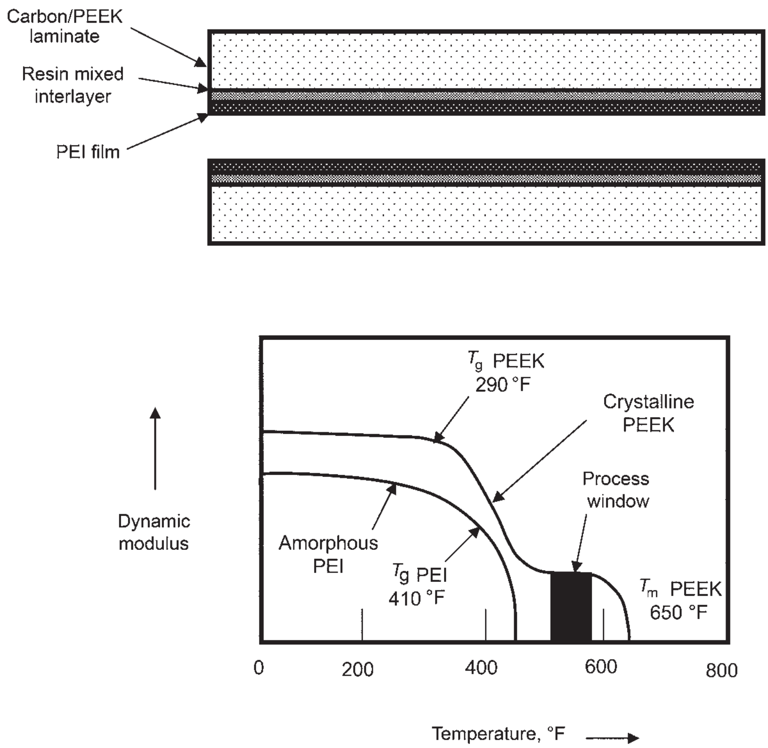


Fig. 10.16 Amorphous or dual-resin bonding. PEEK, polyetheretherketone; PEI, polyetherimide. Source: Ref 10.5

Resistance Welding. In resistance welding, a metallic heating element is embedded in a thermoplastic film and placed in the bond line (Fig. 10.17). This process is used to weld the ribs to the skin for the Airbus A380 wing leading edge. For all fusion welding operations with thermoplastic composites, it is necessary to maintain adequate pressure at all locations that are heated above T_m. If pressure is not maintained at all locations that exceed the T_m, deconsolidation due to fiber bed relaxation will likely occur. The pressure should be maintained until the part is cooled below its T_g.

Ultrasonic Welding. Ultrasonic welding is used extensively in commercial processes to join lower-temperature unreinforced thermoplastics and can also be used for advanced thermoplastic composites. An ultrasonic horn, also known as a sonotrode, is used to produce ultrasonic energy at the composite interfaces to convert electrical energy into mechanical energy. The sonotrode is placed in contact with one of the pieces to be joined. The second piece is held stationary while the vibrating piece creates frictional heating at the interface. Ultrasonic frequencies of 20 to 40 kHz are normally used. The process works best if one of the surfaces has small asperities (protrusions) that act as energy directors or intensifiers. The asperities have a high energy per unit volume and melt before the sur-

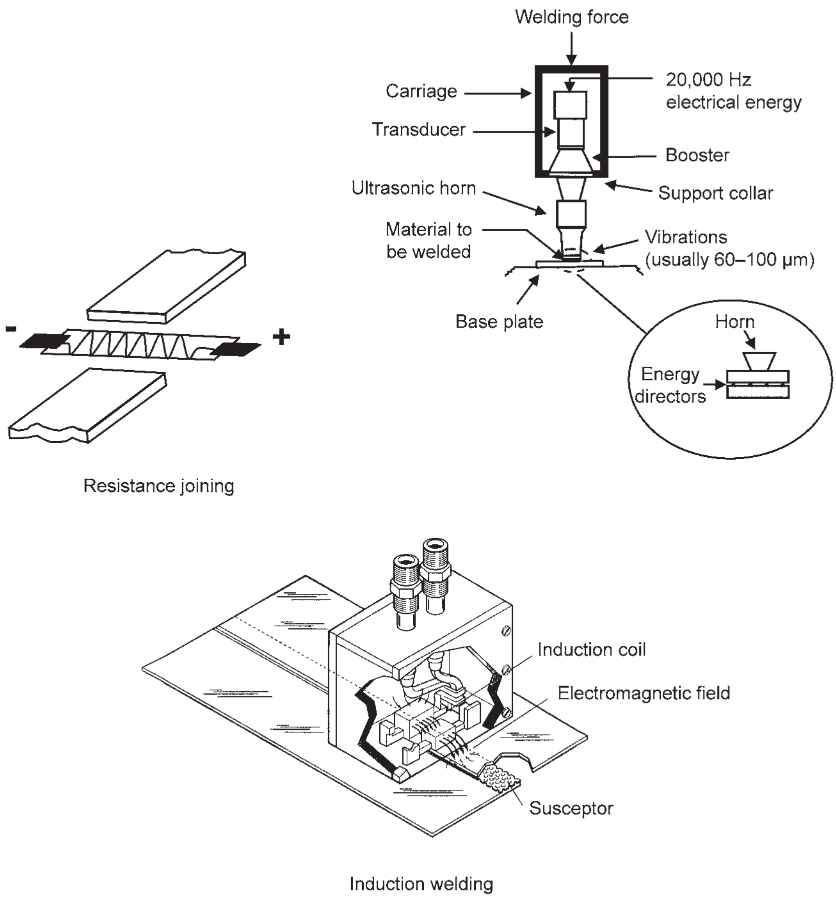


Fig. 10.17 Thermoplastic composite welding methods. Source: Ref 10.5

rounding material. The quality of the bond is increased with increasing time, pressure, and amplitude of the signal. This process is somewhat similar to spot welding of metals.

Induction Welding. Induction welding techniques have been developed in which a metallic susceptor may or may not be placed in the bond line. However, it is generally accepted that the use of a metallic susceptor produces superior joint strengths. A typical induction setup uses an induction coil to generate an electromagnetic field that results in heating due to eddy currents in the conductive susceptor and/or hysteresis losses in the susceptor. Susceptor materials that have been evaluated include iron, nickel, carbon fibers, and copper meshes.

A comparison of single-lap shear strengths produced in thermoplastic composites, using the various techniques described above, is given in Fig. 10.18. Note that adhesive bonding yields lower joint strengths than fusion bonding techniques and is very dependent on the surface preparation

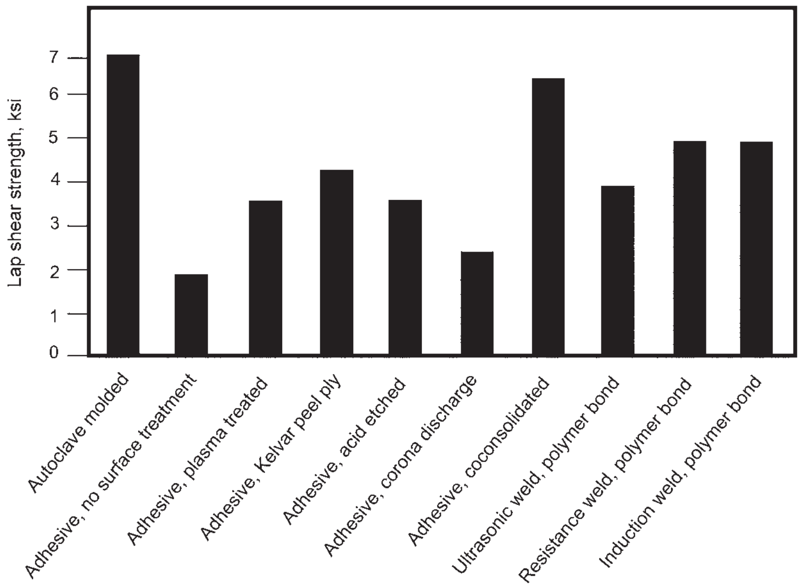


Fig. 10.18 Lap shear strength comparison of different joining methods. Source: Ref 10.5

method used. Autoclave coconsolidated (melt fusion) joint strengths approach virgin autoclave molded strengths. Typically, resistance and induction welding strengths exhibit similar properties, both of which are superior to those of ultrasonic welding.

10.4 Glass-to-Metal Seals

Glass-to-metal seals have a wide range of applications in different engineering and electronic applications. Incandescent and vapor lamps, electron tubes, electrical feedthroughs, and housings for semiconductors are some of the many applications that use glass-to-metal seals. In lamps and electronic tubes, glass is used because it transmits light, can be easily formed into useful shapes, and provides electrical insulation and chemical inertness in corrosive or oxidizing environments. In many applications, an electrical connection needs to be made through a bulkhead that is hermetic, that is, vacuum tight. This requires strong adherence between the glass and metal.

Glass-to-metal seals can be classified in a number of ways. One of the most prevalent methods of classification is based on the level of stress in the glass, for example, matched or balanced, and unmatched or unbalanced. In matched seals, the coefficient of thermal expansion (CTE) of the glass and metal are similar over the entire temperature range of sealing. Sealing is the result of good chemical bonding between the glass and the metal at the interface. Matched glass seals can be made between glasses and metals, ceramics, or other glasses. A typical design of a matched glass-to-metal seal is shown in Fig. 10.19.

In unmatched seals, the CTEs of the various parts are different over the temperature range of sealing. These seals are divided into two groups: compression seals and ductile metal, or Housekeeper, seals. In compression seals, joining is accomplished when the metal establishes a compressive hoop stress on the glass. With these seals, mechanical bonding may be sufficient, but the development of chemical bonding is always desirable. Compression seals are made with only the metals applying the compressive stress. A typical design of a compression seal is shown in Fig. 10.20.

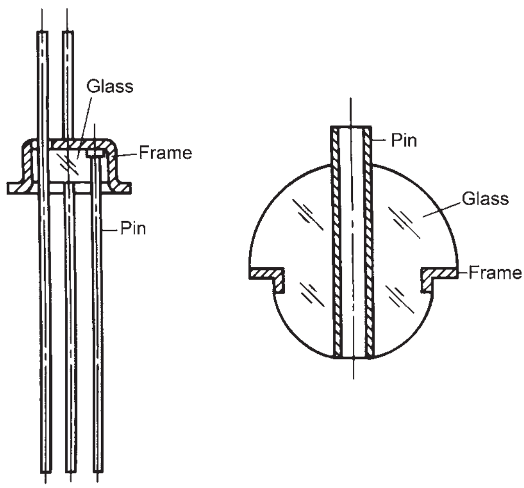


Fig. 10.19 Typical design of matched glass-to-metal seal. Source: Ref 10.6

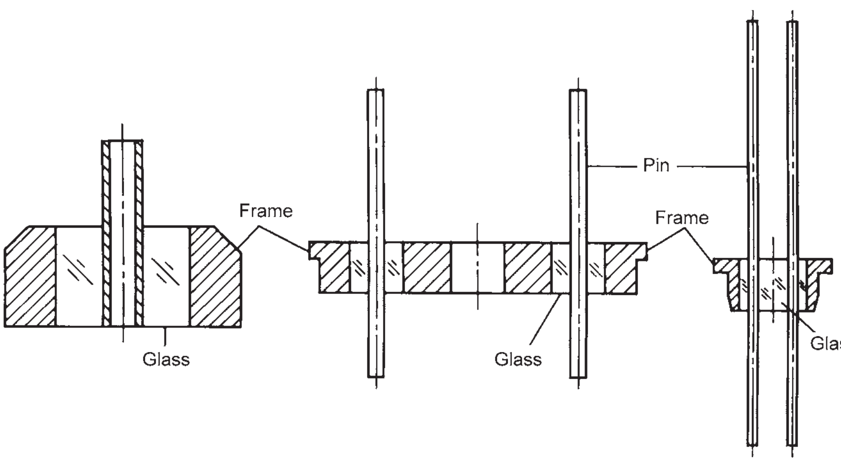


Fig. 10.20 Typical designs of compression glass-to-metal seals. Source: Ref 10.6

Ductile metal, or Housekeeper, seals were introduced by G.W. Housekeeper to join many types of glasses to copper. Figure 10.21 shows typical steps in making a Housekeeper seal between copper and glass tubing. Copper has a relatively high CTE (18×10^{-6}/°C) and does not match any of the usual commercial sealing glasses. However, because of its ductility, copper can be joined to almost any glass, from Pyrex type to iron-sealing glasses, using the Housekeeper seal. Because of its high ductility, if copper is thin enough, it yields under the stresses caused by large CTE differences with sealed glasses, so that no cracking of the seal occurs. These types of seals are now used also with Kovar and several stainless steels. Housekeeper seals require good chemical bonding between the glass and metal.

The basic requirements for strong glass-to-metal seals are chemical bonding and favorable stress gradients in the interfacial zone. It is generally recognized that a number of factors must be controlled if a satisfactory bond or seal between two dissimilar constituents is to be produced. These factors can be grouped into three general categories: physical, chemical, and processing.

10.4.1 Physical Factors in Making Glass-to-Metal Seals

The CTEs of metals are usually considerably greater than those of glasses and ceramics. Thus, the most important requirement in developing a successful glass-to-metal seal is a proper matching of the thermal expansion or contraction characteristics of the bonded materials. Ideally, one strives to develop a slight compressive stress in the glass component of the seal during cooling from the firing or maturing temperature. The compressive strength of glasses usually exceeds the tensile strength by about 10 to 20 times and is approximately 20 to 80 MPa (2.9 to 11.6 ksi).

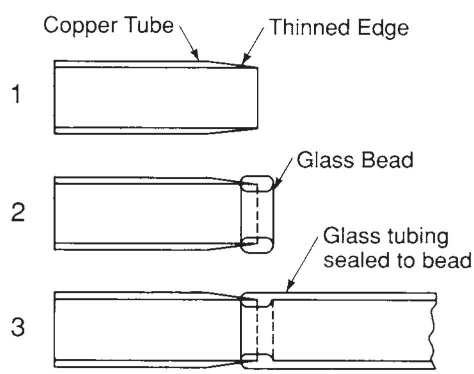


Fig. 10.21 Steps in making a Housekeeper seal between copper and glass tubing: (1) the copper tube has to be thinned; (2) a glass bead is applied to the edge of the thinned copper tube; and (3) the glass tubing is then sealed to the bead. Source: Ref 10.6

Thermal expansion mismatch also results in shear stresses acting along glass-to-metal interfaces that tends to separate the glass from the metal. The bond developed between the glass and metal must be of sufficient strength to withstand these stresses; otherwise, an adherence failure will occur. If the bond is weak, a crack will propagate at the interface causing separation of the bonded components. If the bond is strong and the CTE difference is large, a crack will nucleate in the glass very close and parallel to the interface.

Failure of glass-to-metal assemblies is often thought to start at regions of high residual stress. The interfacial zone between metal and the glass is one region where the high residual stress and flaws can arise. These stresses are mainly due to reactions at the interface and diffusion of the metal ions into the glass. As a result of this process, the properties of the interfacial zone, such as the CTE, glass transition temperature (T_g), and elastic modulus, will more than likely be different from those of the bulk glass.

Residual stresses in glass-to-metal systems arise from several sources, but the dominant one is the difference in CTEs of the metal and the glass, which results in different contractions during cooling from the softening or set point temperature to the use temperature. Thermal gradients in the glass, produced by rapid heating and cooling, can also induce either permanent residual stresses (if the gradient exists during cooling through the set point, that is, thermal tempering) or transient stresses (if the gradient is established at temperatures below the set point). Therefore, residual stresses can be minimized to some extent by control of thermal history. However, residual stresses are also dependent on geometry, and thus actual components should be tested.

Another physical characteristic or factor that is important is the nature of surfaces being bonded. A highly irregular surface finish, produced by either abrasion or chemical erosion, can provide a mechanical contribution to adherence. There is evidence that surface roughness produced by sandblasting or chemical etching of the metal substrate can provide mechanical interlocking and also increase the surface area for glass attachment. Although such interfacial roughening contributes to adherence by producing a more diffuse (wider) transition zone and increasing the contact area, it is not necessary if a chemical bond is attained throughout the interface and the CTE difference is not too large.

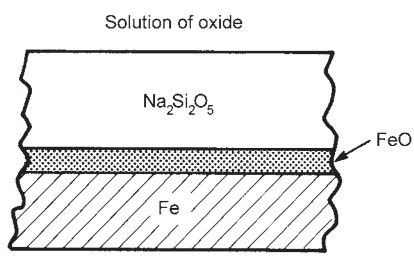
10.4.2 Chemical Factors in Making Glass-to-Metal Seals

The two most important chemical factors in the development of good adherence at glass-to-metal interfaces are (a) the formation of an intimate interface in contact on the atomic level and (b) the reactions reaching stable chemical equilibrium at the interface, which results in chemical bonding. An intimate solid/liquid interface is formed when the liquid glass wets or spreads and thereby penetrates irregularities and distributes itself on the metal surface. Reactions invariably form more stable phases.

Glass-to-metal interfaces generally undergo redox reactions at the interface, that is, oxidation of the metal and reduction of a cation in the glass or ceramic. In the case of an oxide phase, the oxygen released by the reduction of the cation forms an oxide with the metal. Saturation of the interface with the metal oxide and subsequent formation of an oxide layer drives the interface toward equilibrium and results in chemical bonding at the interface. The oxide layer must be compatible with both its parent metal and the glass or ceramic. Commercially, the necessary compatible oxide layer at the interface is normally obtained by preoxidizing the metal, which itself is a redox reaction, before the application of the glass.

The preoxidation procedure for $Na_2Si_2O_5$ glass and iron metal system provides an example (Fig. 10.22). At the oxidation temperature, the molten glass wets and dissolves any oxide on the iron. The glass at the interface immediately becomes saturated with Fe^{2+} because the dissolution rate of the oxide is faster than the diffusion rate of the dissolved oxide into the bulk glass. As a result, chemical bonding at the interface occurs. The oxide layer also bonds chemically to the metal, which in turn is saturated with oxygen, at least at its surface. The saturated interfaces and the oxide layer thus have a chemical activity of one for Fe_xO, which is a requirement for chemical bonding in this system.

The reaction at the interface depends on the relative oxidation potentials of the metal and the cations in the glass. The metals can be arbitrarily grouped on the basis of reactivity with oxygen as low, intermediate, and high. The low-reactivity metals are those with relatively small negative free energies for oxidation and include gold, platinum, and silver. The group of metals that form intermediate-strength oxides includes iron, nickel, and cobalt. The high-reactivity group includes metals such as chromium, titanium, and zirconium.



$$xFeO + Na_2Si_2O_5 \rightarrow Fe_xNa_2Si_2O_{5+x}$$

Fig. 10.22 Schematic cross sections of glass on preoxidized metal, with equation representing solution reaction of oxide by the glass. Source: Ref 10.6

10.4.3 Processing of Glass-to-Metal Seals

Processing factors in producing glass-to-metal seals are very important because they require reproducible control. Processing variables also can control the degree of oxidation of the metal surface, the chemical reaction behavior, and the nature of the strain development in the interfacial zone.

The metals commonly used in making glass-to-metal seals are platinum, tungsten, molybdenum, copper, iron, nickel, and alloys of various proportions of iron, nickel, cobalt, and chromium. Specific sealing glasses are needed for each metal or alloy primarily because of the need for a near match of thermal expansions. Combinations of metal and glass recommended in commercial practice are listed in Table 10.1.

In making a particular seal design, the metal and glass are selected on the basis of specific properties and requirements. The metal is usually selected first based on electrical and thermal conductivity, thermal expansion, ability to be welded or soldered, mechanical strength, and chemical resistance requirements. The glass is then selected based primarily on electrical resistivity, dielectric strength, low gas permeability, environmental stability, and thermal expansion characteristics.

In general, the CTE of the glass and metal should be within 10% of each other, with that of the metal being higher for conventional ring-geometry seals. If the difference in contraction is <100 ppm, the stress level will be quite safe, and even 500 ppm usually is satisfactory. A seal with a contraction difference between 500 and 1000 ppm can still be used but only for progressively smaller and thinner assemblies. However, a close match in expansion coefficients is not as critical for thin glass coatings as for bulk specimens.

Glasses for sealing are usually prepared by melting oxides, carbonates, and hydroxides. One of the advantages of the glass materials is their ability to be made easily into a variety of shapes by casting, rolling, blowing, extrusion, and molding. The method used depends on the particular sealing technique. Specific examples of forms used for sealing are tubing, cast preforms of various shapes, and pressed powder preforms.

Table 10.1 Recommended glass-to-metal seal combinations

Metal or alloy	Corning glass code No.	Schott glass No.
Tungsten	7720, 3320, 7750	8486, 8487
Kovar	7052, 7056, 7050, 7040	8454, 8436
Molybdenum	7052, 7056, 7050, 7040 1720, 1723	8250, 8245
Dumet, No. 4 alloy, or platinum	0, 120, 0010, 0080, 9010	8095, 8531, 8532
Fe-28%Cr	7570	
Fe-17%Cr	9019, 0129	8418
1010 steel	1990, 1991, 0110	8422

Source: Ref 10.6

In preparation for sealing, the metal and glass parts are thoroughly cleaned, primarily to remove organics that normally interfere with wetting of the metal by the glass. Organics also form CO and CO_2 on reaction with oxides in the glass, which produce bubbly seals that do not have a very good appearance, are weak, and may not be hermetic if the bubbling is severe. The usual method of removing organics is to oxidize them by heating in a wet hydrogen atmosphere to about 1100 °C (2010 °F). The cleaning can also achieve some etching or roughening of the metal surface. The clean metal is then preoxidized if the amount of oxidation that will occur during the sealing process is insufficient for good bonding.

The glass parts to be sealed frequently are provided as preforms. Those preforms are fixtured with the metal parts and then heated to a temperature above the softening point of the glass. During the thermal cycle it is essential that the glass should dissolve most of the surface oxide on the metal in order to form a bond with the metal. In most cases the amount of oxide, which is controlled by the time and temperature of its formation, is the principal factor in developing good adherence. If the oxide layer is too thin, upon its solution by the glass, chemical bonding is lost and the seal has poor strength (although it may be vacuum tight, especially under compressive stresses). If the oxide layer is too thick, a certain amount of the oxide may remain after sealing, and the strength of the seal is affected by the strength of the oxide and its adherence to the metal. Also, if the oxide layer is continuous and porous, the seal may not be vacuum tight. The temperature-time conditions under which flaking of the oxide on Kovar is most apt to occur are shown in Fig. 10.23. Such flaking results in poor adherence.

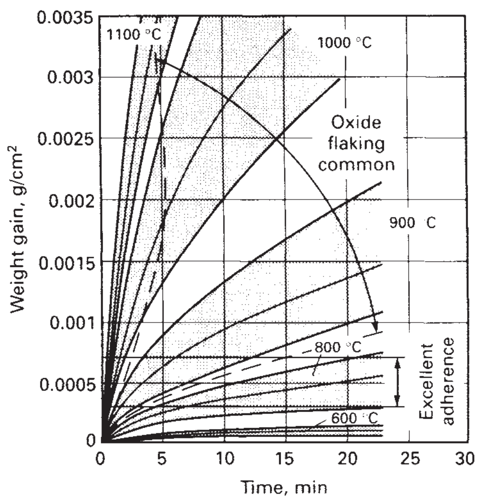


Fig. 10.23 Oxidation as a function of time and temperature for small pieces of Kovar. The area inside the V-shaped dashed curves indicates conditions under which the greatest tendency for oxide flaking exists. Source: Ref 10.6

After the seal is made, the assembly is cooled to room temperature. The critical range for cooling is just below the transformation temperature of the glass. The assembly must be annealed or slowly cooled through this range in order to avoid destructive thermal strains in the glass. The importance of annealing increases with an increase in the glass thickness.

10.5 Joining of Ceramics

Mechanical and adhesive joining of ceramics can be useful for low-temperature, low-stress applications. However, to take advantage of the high-temperature capability of ceramics requires some type of diffusion bonding or brazing operation. The highest temperature capable joints will be made with straight diffusion bonding. However, since diffusion bonding of ceramics requires high temperatures and pressures, more practical but lower-temperature bonds are often made with metallic interlayers that either do or do not form liquids at the bonding temperature.

10.5.1 Joining Oxide Ceramics

Ceramics can be broadly classified as either oxide ceramics (e.g., Al_2O_3) or nonoxide ceramics (e.g., SiC). While the processes for both types are similar, there are differences in materials and procedures as a result in their difference in chemical composition.

Oxide Ceramic-Ceramic Joints. Diffusion bonding is usually performed at temperatures and pressures where at least one component plastically deforms under the applied load so that the surfaces are brought into intimate contact. Although the material that deforms in most cases is either the metal portion of a ceramic-metal joint, or an intermediate material placed in the joint, it may also be the ceramic. Coarse-grained oxides are generally difficult to join to themselves and require a material that deforms more readily during bonding, such as a finer-grained material of the same or different composition. The level of dopant also affects bond quality, because higher levels usually result in finer grain size. A combination of cold isostatic pressing and hot isostatic pressing can also be used to join oxides. This requires ceramic green bodies having similar green density and sinterability, in addition to a relatively high green body strength.

Brazing with filler metals is an attractive process for joining structural ceramics for many applications. Wetting and adherence are the principal requirements for brazing; however, most ceramics are not wetted by conventional brazing filler metals. This problem can be overcome either by coating the ceramic surface with a suitable metal layer before brazing (indirect brazing) or through the use of specially formulated filler metals that wet and adhere directly to an untreated ceramic surface (direct brazing).

Indirect brazing involves coating the ceramic in the joint area with a material (usually a metal) that can be wetted by a filler metal that would not wet the untreated surface. Coating techniques include sputtering, vapor plating, and thermal decomposition of a metal-containing compound, such as TiH_2. The most widely used brazing technique for joining alumina ceramics is the moly-manganese (Mo-Mn) process (Fig. 10.24). The ceramic surface is initially metallized and then brazed to metal using one of various brazing filler metals. The chemical composition and properties of the glassy phase in the moly-manganese layer are very important. Glass or ceramic additions are made to this layer, based on the composition and properties of the ceramic, in order to achieve better compatibility.

During direct brazing, the wetting of an untreated ceramic by a molten metal and the associated adhesion increase with growing affinity of the metal constituents for the elements constituting the solid phase. Thus, chemically oxygen-active metals such as titanium, zirconium, aluminum, silicon, manganese, or lithium, either pure or alloyed with other metals, enhance both wetting of and adherence to oxide ceramics, without the need for coating the ceramic surface. Whether the ceramic is an oxide,

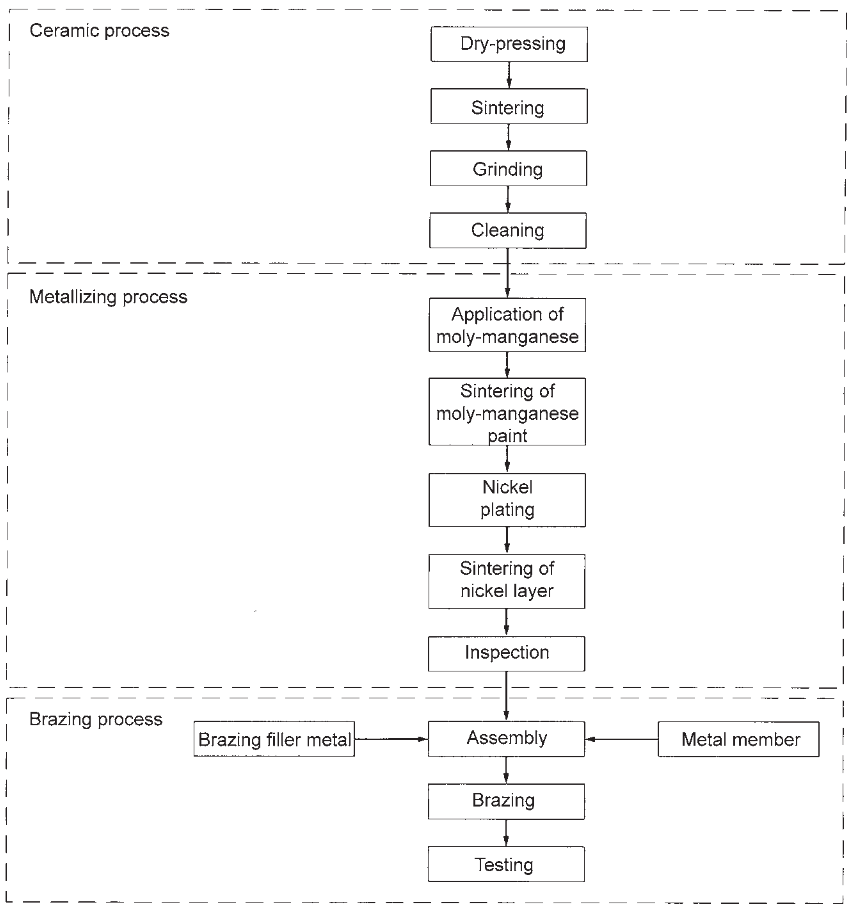


Fig. 10.24 Typical steps in the moly-manganese process. Source: Ref 10.7

carbide, or nitride, the active metal reacts with the ceramic surface, forming an interfacial layer that can be wetted by the bulk of the filler metal. Titanium is the most extensively studied and widely used active element addition to filler metals formulated to directly braze high-melting oxide ceramics. The critical interfacial reaction product in the case of oxide ceramics brazed with titanium-containing filler metals is either TiO or Ti_2O_3, with appreciably higher adhesion in systems that result in the formation of TiO.

The four primary variables in direct brazing of ceramics are (a) active element content of the filler metal, (b) brazing time, (c) brazing temperature, and (d) the surface condition of the ceramic. In general, as the primary variables are increased, the strength of a joint increases to a peak value and then decreases (Fig. 10.25). This behavior can be explained on the basis of the formation and growth of the reaction products at the interface between the ceramic and filler metal. These products are a necessary part of the wetting and adherence process, but if the reaction products grow excessively, the bond may be weakened. It is assumed that flaws are created by the stresses and strains associated with the volume changes that occur when the reaction products are formed and grow, and that these flaws result in the observed degradations of joint strength.

Oxide Ceramic-Metal Joints. Both ceramic-ceramic and ceramic-metal joints have been fabricated using diffusion bonding. Most of the work has been on ceramic-metal joints in which the metal portion of the joint is a bonding material added to either the interface between two ceramic components or the second member of a bimaterial joint. For instance, alumina has been joined to a nickel-based superalloy at a pressure of 150 MPa (20 ksi) and a temperature of 1300 °C (2370 °F). Ceramic-ceramic diffusion bonding and a variation on this process, in which ceramic powder compacts are simultaneously sintered and bonded (sinter-bonding process), have also been developed.

Two types of interaction have been observed in diffusion bonding of ceramic-metal joints. In the first type, bonding is driven by a decrease in

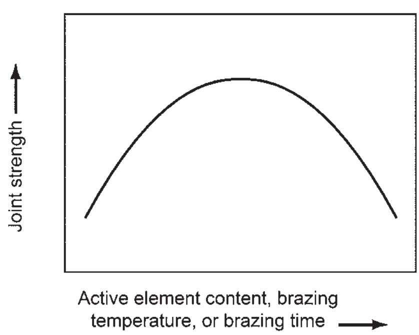


Fig. 10.25 Relationship between joint strength and primary brazing variables for structural ceramics joined by active filler metals. Source: Ref 10.7

surface energy as a new interface is formed to replace the two original surfaces. This physical interaction is indicated by an abrupt transition in microstructure between metal and ceramic at the interface. Examples of this type of bond are those between alumina bonded under high vacuum to aluminum, copper, nickel, platinum, and niobium. However, under certain conditions of temperature and excess oxygen activity, reaction products can form at some of these interfaces.

In the second type of solid-state bond between ceramics and metals, chemical reaction further lowers the energy of the system and increases the strength of the bond. Chemical reaction product layers are observed in the joints after bonding. These reaction products generally cause stronger bonds; however, weakening of the joint may occur if the reaction products grow to excessive thicknesses during bonding or in service. Diffusion bonds between oxide materials and metals that result in the formation of interfacial reaction products include alumina with aluminum, aluminum and magnesium with SiO_2 and ZrO_2, nickel with MgO, and nickel and titanium with Al_2O_3.

The temperature required for diffusion bonding usually ranges from 0.5 to 0.8 of the absolute melting point of the ceramic, the metal being bonded to the ceramic, or an interlayer that is added at the interface to promote bonding. A wide range of applied pressures has also been used, ranging from 15 kPa to 200 MPa (3 psi to 29 ksi) and higher. The surface finish of the mating materials is also a critical variable, because the success of the process depends on the attainment of intimate interfacial contact. If all other variables are equal, rough surfaces require greater pressures to force the surfaces into contact for bonding.

10.5.2 Joining Nonoxide Ceramics

Conventional joining research and development for ceramics has concentrated on oxide ceramics. The use of the molybdenum-manganese metallizing method is well established in industry for joining alumina. However, this method cannot be used for nonoxide ceramics, because it is based on the reaction between glass-forming compounds in the paste and the glass grain boundary phase of the alumina ceramic. A glass phase suitable for this reaction does not exist in nonoxide ceramics. Thus, a number of alternative joining techniques have been developed for nitride and carbide ceramics.

Nonoxide Ceramic-Ceramic Joints. Joining a silicon-based ceramic to itself can be performed using metallic interlayers. For example, laminated interlayers of nickel and Ni-Cr alloy have been used to join silicon nitride to itself. Laminated interlayers can produce higher bond strengths compared to a single interlayer. The main advantage of using metal interlayers is that it becomes possible to reduce the temperature, pressure, and time required for joining. However, with interlayers, it is generally not possible to have both heat resistance and oxidation resistance in a joint at the same time. Direct diffusion bonding without any metallic interlayer gives joints that are stable at temperatures >1000 °C (1830 °F); however, this technique is impractical for many situations.

Hot isostatic pressing without any interlayer under isostatic pressures >100 MPa (15 ksi) can give a nearly ideal joined interface. Complete contact at the interface can be achieved, and the interfacial region may have the same structure as the matrix. When the silicon nitride contains a large amount of sintering additive, the additive may concentrate in the interface region during joining, which can reduce high-temperature strength. Uniaxial hot pressing is another way to achieve solid-state joining without an interlayer. In the hot pressing process, the pressures are limited to much lower values than in hot isostatic pressing, because the uniaxial pressing can easily cause large deformations of components. The high processing costs of solid-state bonding may prevent its wide application, but several cost-saving improvements have been reported. Microwave heating of the interfacial region promotes joining and has been used for silicon nitride. This method does not require conventional furnaces, and joining can be completed in a short time. Joint strengths of up to 500 MPa (70 ksi) have been achieved.

Silicon carbide is a difficult material to join by solid-state methods, even by hot isostatic pressing. A silicon braze or TiC interlayer, plus aluminum foil, has been used to join sintered silicon carbide and reaction-bonded silicon carbide, respectively. These two materials have been bonded without any interlayer. Joining by reaction sintering of silicon carbide further reduces the joining temperature. In this technique a powder mixture of silicon carbide and carbon is used as the joining interlayer and is siliconized at 1450 °C (2640 °F). A similar method uses capillary infiltration of molten silicon into tape-cast SiC-C powder precursor interlayers to produce reaction-bonded silicon carbide interlayers. Both methods achieve bond strengths at pressures >300 MPa (40 ksi) that are maintained at temperatures of ≥1400 °C (2550 °F).

Nonoxide Ceramic-Metal Joints. The interfacial microstructures of silicon nitride and metals are generally divided into three types, based on their reaction processes. The first type is the interface made by active metal brazing, which is one of the most popular joining processes for ceramic-to-ceramic or ceramic-to-metal systems. The second type is formed by a eutectic melting reaction between silicon-based ceramics and metals. Silicon-based ceramics react with some transition metals to form eutectic liquids. The method uses this eutectic reaction by optimizing the reaction conditions. The third type is formed by complete solid-state reactions under pressure.

Active metal brazing materials, which contain a small weight percent of active elements such as titanium, are available for silicon-based ceramics. Several kinds of active filler metals have been examined. Silver-copper eutectic alloy with a small weight percent of titanium or zirconium, copper-titanium eutectic alloy, and pure aluminum and aluminum-titanium alloy have been examined for use with silicon nitride. Silver-copper-titanium alloy, nickel-titanium alloy, and aluminum have been explored for use with silicon carbide.

Brazing with the silver-copper-titanium alloy is a typical process that is accomplished without any metallization. The constituents of the joint are fixed in a furnace, and a slight load is applied. They are then held at the brazing temperatures for Ag-Cu-Ti filler metals, which range from 800 to 950 °C (1470 to 1740 °F). The brazing atmosphere is either a vacuum below about 0.0133 Pa (10^{-4} torr) or an inert gas, such as high-purity argon. The maximum interfacial strength obtained using the Ag-Cu-Ti filler metals exceeds 500 MPa (72.5 ksi), as measured by the four-point bend test.

Eutectic reactions can also be used for joining. Most metallic materials react with silicon ceramics to form eutectic liquids between the silicon and the metal. These reactions can be used for joining. The eutectic reaction temperatures, which are primarily determined from the two-component phase diagrams of metal silicon systems, are about 1100 °C (2010 °F) for nickel and its alloys and about 1200 °C (2190 °F) for iron and its alloys with silicon nitride. For silicon carbide, the temperature ranges are lowered by 50 to 100 °C (90 to 180 °F) by the presence of carbon, and the reactions are much more extensive than in silicon nitride. The presence of oxygen in the reaction atmosphere may lower the temperature of liquid formation. Reaction layers are formed at the interface in these systems. The reaction products are mainly metal silicides when silicon nitride is joined. High-temperature strengths of silicon nitride joints, one of the critical properties required for high-temperature applications, are shown in Fig. 10.26.

During solid-state bonding, refractory metals such as molybdenum, niobium, tantalum, zirconium, and tungsten, react in the temperature range between 1300 and 1500 °C (2370 and 2730 °F) with silicon ceramics by solid-state processes to form strong interfaces. The maximum interfacial strength with solid-state bonding is achieved by the optimization of time, temperature, and pressure. It is possible to achieve an interfacial strength above 300 MPa (45 ksi) for silicon nitride/refractory metal systems. In solid-state bonding, the pressure has a great influence on the completeness of the contact at the interface. Isostatically applied high pressure is the most effective means for obtaining full contact.

ACKNOWLEDGMENTS

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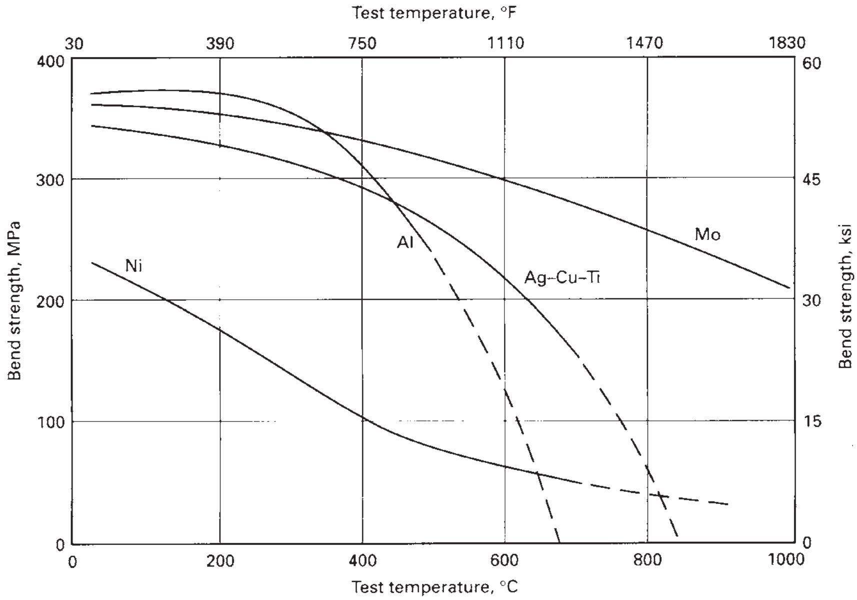

Fig. 10.26 High-temperature strength of silicon nitride joints fabricated using various interlayers. Source: Ref 10.7

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